NASA CR — 86316

Optimization of Microwave Radiometric Systems For Earth Resource Surveys

By H. I. Ewen and A. H. Barrett

June 1969

Prepared under Contract No. NAS 12-2047 by
EWEN KNIGHT CORPORATION
East Natick, Massachusetts 01760

Electronics Research Center
National Aeronautics and Space Administration
Cambridge, Massachusetts 02139

EWEN KNIGHT

14

NASA CR-

OPTIMIZATION OF MICROWAVE RADIOMETRIC SYSTEMS FOR EARTH RESOURCE SURVEYS

By H. I. Ewen and A. H. Barrett

JUNE 1969

FINAL REPORT

Prepared under Contract No. NAS 12-2047 by
EWEN KNIGHT CORPORATION
EAST NATICK, MASSACHUSETTS 10760

ELECTRONICS RESEARCH CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CAMBRIDGE, MASSACHUSETTS 02139

ACKNOWLEDGMENT

The information and assistance provided by personnel in Government and private organizations concerned with the Earth Resource program was of immense help in the conduct of this study and is greatly appreciated. We particularly appreciate the considerable amount of personal time devoted to this effort by the following NASA, ERC personnel:

Dr. Gene G. Mannella

Dr. Alfred E. Barrington

Mr. Glenn S. Larson

Mr. Arthur E. O'Brien

Ewen Knight personnel who were responsible for various aspects of the study include:

Dr. H. I. Ewen and Dr. A. H. Barrett (MIT), Co-investigators

Mr. E. Lee, Program Coordinator

Mr. E. J. Chaisson, Model Analysis

Mr. H. P. Taylor, Radiometer System Analysis

In addition, the following group of consultants provided guidance in certain aspects of the study involving special areas:

Dr. David H. Staelin, Assistant Professor of Electrical Engineering, MIT

Dr. Ferd H. Mitchell, Professor of Physics, University of South Alabama

Dr. Jack Copeland, Professor of Physics, University of South Alabama

TABLE OF CONTENTS

LIST OF FIGURES

1.0 INTRODUCTION

Objectives

This report describes the results of a study and investigation to determine methods for optimizing the contribution of microwave radiometers in Earth Resource applications. Earth Resources include both natural and cultural resources. Natural resources are defined as those naturally occurring materials, such as mineral deposits, timber stands, and fresh water, which are of value to mankind. Cultural resources are defined as those items of value to man, which result from his own activities. As such, they encompass all of the beneficial works of man and, as so defined, include man himself. Cultural resources are in general derived from natural resources.

The Earth Resource program objective is to gather natural and cultural resource data with spaceborne instruments in an operational, repetitive manner for use by scientific, technical and commercial interests.

Today, many important decisions are made by choosing a quantitative measure of effectiveness - and then optimizing it. Deciding how to design, build, regulate, or operate a physical or economic system, ideally involves three steps:

> First, one should know accurately and quantitatively how the system variables interact.
>
> Second, one needs a single measure of system effectiveness - expressible in terms of the system variables.
>
> Finally, one should choose those values of the system variables yielding optimum effectiveness. Thus optimization and choice are closely related.

As is frequently the case, and certainly in this study, the work expended in defining the decision problem, gathering reliable data, and agreeing on objectives, far exceeded the effort devoted to defining the optimum approach. Though a decision without optimization is as unfinished as an arch without a keystone, optimization, like a keystone, is only a small part of the total structure.

Approach to the Investigation

The purpose of this investigation was to develop a research and engineering plan describing methods for optimizing passive microwave radiometric sensor systems in Earth Resource applications. Three areas were identified at the outset of the study as candidates for the investigation of more optimum methods. These were:

Analytical models

Supporting measurements

Measurement instrument performance characteristics

By concentrating the investigation on these three areas, our objective was to define a research and engineering program which would:

Provide an improved understanding of the microwave radiation characteristics of materials under natural environmental conditions.

Directly aid and assist User Agencies in determining the radio signature characteristics of materials under various conditions.

Identify measurement instrument performance requirements best-suited to the detection of anticipated radio signature characteristics associated with terrain materials under natural environmental conditions.

It was recognized at the outset of the study that the research and engineering plan would, in large part, be predicated on a survey of available information concerning User requirements and the potential application of microwave radiometry to these requirements, based on published results of analytical studies and supporting measurements. As a result of this survey, we hoped to derive:

> A definition of User requirements in terms of specific material characteristics and associated spatial and temporal resolution needs.
>
> A description of possible relationships between the thermal radiation characteristics of materials and the composition and condition of materials which support the reasonableness of deriving material composition or condition from remote sensing of radio emission characteristics.

In summary, a logical work-flow was established at the outset of the study to ensure that its purpose was accomplished. As we proceeded, there were several surprises that were totally unanticipated. We feel they are worthy of particular note since they have a significant bearing on the conclusions reached as a result of this investigation.

We learned that the degree of surprise associated with the unanticipated is frequently directly related to the degree of confidence one has in the anticipated. Both co-investigators are Microwave Physicists. Certain results were anticipated at the outset of the investigation. We later recognized that these first anticipations were derived from an approach to analyzing natural behavior, which is common to our discipline. In a purely scientific approach, one normally reverses the order of the three steps for rational decision-making. Knowledge about a system is deduced by assuming it behaves so as to optimize some given measure of effectiveness. Thus, system behavior is completely specified by identifying the criterion of effectiveness, which then leads to a description of natural behavior in terms of an "optimum principle." From this viewpoint, optimum methods would be those best-suited to arrive at an improved understanding of natural phenomena.

Though improvement in knowledge concerning natural phenomena is a laudable and useful product of pure scientific research, it soon became apparent that if each discipline associated with the Earth Resource program effort were to approach its contribution to the total effort in this somewhat detached manner, we might as a group ultimately reach the top of the mountain - though the time required would be excessive in comparison with a coordinated effort.

There are many paths to the top of a mountain; and whatever route a mountain-climber takes, he recognizes the peak when he arrives there - because the view there is always the same. These simple facts, intuitively evident where mountains are concerned, are not so easy to preceive and quantitatively define for political or social systems. In these cases, an isolated discipline approach to mountain climbing runs the risk of making an insignificant contribution, since there are many methods for finding the peak without mapping the entire mountain.

Our zeal for economy of thought clearly led us to over-simplification of the problem in the early phase of the investigation. We proceeded on a straightforward course to the definition of methods for empirical measurement and supporting analysis which would lead to an improvement in present knowledge concerning the microwave radiation properties of materials in the most fundamental sense. Thus we arbitrarily established the Second Step in the decision-making process as an effective means for improving scientific knowledge. We had established understanding as the most useful end product. Fortunately, our survey of User requirements, available analytical models, and the results of prior measurements was proceeding at a rapid pace in parallel with our development of what we felt would be an optimum analytical and supporting measurement program. From the survey portion of the effort, we learned that a detailed understanding of physical phenomena was not mandatory to the useful application of microwave radiometry for Earth Resource Applications. Water had many useful applications for man long before an understanding of its molecular structure was developed. A more detailed understanding of the water molecule continues to be pursued; however, the many applications do not await this detailed understanding.

At this point in the investigation, we re-defined the measure of the system effectiveness as - a data collection and usage mechanism, which is simple and reliable and provides maximum benefit to the greatest number of Users. We then directed an intensive effort on the First Step in a decision process; i.e., how the system variables interact, since this would provide a definition of the most useful contribution that could be made from the isolated vacuum of our own discipline. This naturally led into an investigation of interdisciplinary involvement.

Interdisciplinary Involvement

This phase of the investigation was particularly important. We had reached an impasse - convinced that our original thoughts concerning a useful contribution were in error, and there appeared to be no equally reasonable and logical alternative approach. However, two important actions then taken served to provide a solution for our dilemma:

(1) Intensification of our effort to determine User requirements through a series of direct personal visits.

(2) Preparation of a questionnaire which we circulated among scientific and engineering personnel in our own microwave discipline.

Prior to visiting User Agencies, we prepared a questionnaire which we felt would provide a definition of User requirements in a relatively simple and logical manner. The questionnaire was not mailed to the Users, but was used as an outline to be completed by one of our associate team members during each visit. The method was totally ineffective. Sufficiently detailed answers were not available. There was considerable enthusiastic support for the potential of passive microwave sensing expressed by all Users. User reluctance to state requirements in specific detail appears to be associated with a natural desire not to express a requirement that might be shown to be physically unrealizable on the one hand, nor to ask for less than might be potentially possible on the other. This in part was indicative of a lack of familiarity with microwave physical phenomena as well as the associated instrumentation, in the most fundamental sense.

Though our questionnaire approach was designed to provide us the answer to the most effective contribution that could be made by those associated with the microwave radiometric discipline, we found that it is not easy for professionals to agree on a unique measure of effectiveness. In the words of Confucius: "Those whose courses are different can not lay plans for one another." As a result it was apparent from this study that the interdisciplinary capabilities required to achieve the common objective must be organized in a common effort which coordinates the contributions of each discipline.

One objective of our discussions with User Agency personnel was to determine a schedule of application priorities. Certain features of the responses were common to all Users. Application priorities are stimulated by two factors - immediate benefit or impact and degree of confidence in the data collection mechanism. Confidence did not necessarily require understanding of the phenomena or the instrument. Experimental assurance that the data display would be useful in a "yes or no" sense concerning some important feature of the terrain under surveillance, was the most important criteria of confidence. This general trend of opinion among Users emphasizes the importance of establishing a much more effective technological tie between the User and the data-gathering and usage mechanism, and represents a real need in the present phase of the Earth Resource program. It will not be achieved without difficulty. It is natural for the User to look ahead to the future operational system in which the technological complexities have ideally been reduced to simple "yes" or "no" responses to the questions he may ask, since he can at that point ignore the technologies which serve him just as an automobile driver can choose to ignore the fundamentals of internal combustion engines.

The need for a vigorous technological link between the various research disciplines and the User Agencies is one of the prime conclusions of this study. In simple terms, the User is the customer. He is the one who determines what is useful. Most all will agree that it is useful to explore data-gathering mechanisms which may be potentially more useful than those now available. We must also agree that the key participant in this exploration is the one who determines usefulness - in this case, the User Agencies in their composite. This responsibility cannot be assumed by individual research disciplines, since they are not sufficiently multi-discipline oriented to solve the whole problem. An individual research discipline, representative of some required capability in the exploratory phase, could conceivably be more effective in delaying the solution than contributing to it, if the effort is not properly coordinated and directed.

The ineffectiveness of our questionnaire approach to the User was quite clear. To aid in our understanding of what we had learned and add confidence to our conclusions, we prepared another questionnaire for microwave physicists and engineers. Our objective was to identify through a series of simple questions and answers, the interdisciplinary roles of research disciplines, such as our own (microwave physicists), with User Agencies.

The first series of questions in this new questionnaire dealt with Parametric Displays. The first question in this series was to list those parameters which most frequently enter into a parametric display of brightness temperature. The answer is frequency, two orthogonal polarizations, and look angle.

The next question was to identify the basis for the choice of parameters as either: analytical model studies of the emission characteristics of radiating materials, or the parameters available from an instrument standpoint. It is interesting that the answer is that one can derive the parameters from either analytical model studies or by merely noting that a microwave radiometer is equipped with an antenna system which provides a certain angular resolution, can be pointed in a desired direction, and will accept only one polarization at a time, though two polarizations are required to completely define the incident radiation. Further, the radiometer can be designed to operate at any desired frequency.

The third question was to identify the observing platform most commonly used for parametric displays. The answer is earth-based observing platforms. Though aircraft measurements of this type have been performed, the present methods for data accumulation and display are extremely tedious and time consuming.

The questionnaire turned next to the subject of Image Displays.

The first question in this series was to identify the parameters which are normally displayed. The answer, based on present day imagery systems, is that each element of a map type display provides information only for one frequency, one look angle, and one polarization. The next question asked the value of image displays in light of the fact that the ability of a microwave physicist to interpret a display of this type is considerably limited in comparison with a parametric display. The simple answer is User preference, based on his data usage requirements developed from years of experience with optical photographs and more recently, infrared maps.

At this point in the questionnaire, microwave physicists and radiometer engineers have the uneasy feeling that they would prefer not to continue, since their "ivory tower" discipline has been challenged by what appears to be an illogical chain of events. This first series of questions and answers unveils the difference between the researcher devoted to methods for improving knowledge and the fact that the knowledge gained may be of little immediate value if it is not immediately adaptable to the User's requirements.

The next series of questions was designed to emphasize the fact that the User is the customer, that understanding of the radiation properties of materials or radiometric instrument fundamentals was not required by the User in decisions concerning a useful application. These questions emphasized that the availability of theoretical models and supporting measurements, leading to improved understanding of natural phenomena, is not necessarily immediately useful or even competitively desirable if applicability to a User requirement can be demonstrated by an approach which would require less time and effort.

The third series of questions concluded with the identification of earth-based measurements as devoted primarily to the pursuit of improved understanding of the natural phenomena of terrain material radiation - a useful pursuit within itself, but not requisite to an optimum contribution by a researcher in the present phase of the program. Ultimately, this understanding must be developed. It is most likely that the motivation will come from the User. Initially satisfied with "yes" and "no" answers, the grey areas in between will ultimately press for need to understand and through that avenue, obtain an improvement in "usefulness."

The fourth series of questions was devoted to the identification of the logical role of participants in making decisions at critical points in the program. Conclusions drawn from this series of questions were as follows:

> Selection of the data display should be made by the User as a consequence of his usage requirements.
>
> Sensor requirements and approach should be determined by the associated research disciplines.
>
> The scheduling and performance of measurements should be under the direction and include direct participation by the User, since the User is best-qualified to determine the time for a useful measurement; i.e., the conditions of interest.

The final series of questions was presented in the form of a current status review. It was noted that:

> Data displays (in particular, image displays) are improving rapidly - both in popularity and technique. Parametric displays on the otherhand, which are much more closely allied with analytical models, are not being vigorously pursued. The reason is an inadequate level of interest on

the part of Users in data displays of this type. Lack of interest may be directly attributable to lack of understanding. The researcher should provide this understanding to the User. It is equally important that the User appreciate the need for this cross-fertilization between disciplines in the performance of the User's multi-discipline role in the critical exploratory phase.

Though the responsibility for sensor design is the responsibility of the researcher, evaluation of current status led to a very poor rating. Present imaging systems, for example, develop maps in only one polarization - though two are required to completely define the characteristics of the radiation incident on the sensor antenna aperture.

The variation of brightness temperature with incidence angle is virtually eliminated from consideration in a map type presentation. The sensitivity of present-day aircraft imaging systems is limited by the use of techniques that are less than optimum. To overcome these limitations however would require development.

It would appear that present-day sensor systems evolved from available equipments and techniques with a minimum of influence by physical phenomena considerations. This is evidenced by the complete exclusion of the low frequency region, though the wavelength of operation is known to be one of the most potentially important observing parameters.

The genius of hindsight can frequently be misleading. It is important to recall that the first airborne radiometer was flown slightly more than one decade ago. The associated instrument technology is in its mere infancy in comparison with optical and infrared sensors. The courage to fly the available has provided much of the knowledge on which one can now proceed. As in the mountain climbing exercise, the very first step is the most exploratory. It tells us the slope of the mountain and whether we are going up or down. These early measurements have accomplished this result. We are now at the point where we can take those steps which will take us along the shortest route to the top of the mountain.

Continuing with our question series, on current status, it was of interest to note that:

> Measurement schedules are most frequently determined by researchers representing an individual discipline or by aircraft operating personnel, though we had logically identified the multi-discipline User with this responsibility.

The most significant conclusion reached through this questionnaire exercise was the need for greater User involvement and direct participation in the present exploratory phase. The User cannot remain loosely coupled to the exploratory development of an advanced data collection and usage mechanism relying on the efforts of isolated research disciplines. The multi-discipline capability represented by the User is the cohesive force required to gather the composite effort to maximize the return in the shortest time. Direct participation in the most literal sense is strongly indicated.

A simple example may aid in clarifying our meaning. Consider the following alternative approaches in the implementation of an oceanographic measurement program.

In one case, the principal investigator might be a microwave physicist familiar with radiometer technology and the related measurement techniques. In the extreme case, he might rent an aircraft, equip it with radiometric sensors, and perform a series of measurements. His results would be published in a technical journal and, perhaps, presented at a seminar attended by oceanographers. If a useful application to oceanography were suggested as a result of these published reports, the measurements would, undoubtedly, be repeated by oceanographers in order to provide the confidence required to suggest the deployment of a system for their use.

In the alternate approach, the principal investigator would be an oceanographer. The experiment would be planned under his direction and in cooperation with a microwave physicist. Both the oceanographer and the microwave researcher would participate in the performance of the measurement. The usefulness of the experimental technique to oceanography would be determined by the oceanographer. Interpretation of the results, from the microwave viewpoint would be provided by the microwave researcher. A description of the experiment and its significance would be presented by the oceanographer to the oceanographic community through technical journals and seminars.

The second approach offers the following advantages:

(1) The experiment plan is developed with the expertise of the oceanographer, the prime beneficiary of the results.

(2) Throughout the experiment from the planning phase through equipment assembly, accumulation of observational data and data analysis, an interdisciplinary technological interchange would be fertilized by the joint participation of professionals in a common venture. Skepticism would be replaced by confidence through personal interchange, leading to a mutual understanding of the problem and the significance of the results.

(3) Presentation of the results to the oceanographic community by a competent well-recognized oceanographer would provide an avenue of acceptance by the oceanographic community which would negate the need for repetitive measurements nurtured by a lack of understanding.

2.0 SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

A summary of the conclusions and recommendations resulting from this study are presented below.

2.1 Conclusions

Based on the results of the study of methods which would optimize the contribution of passive microwave radiometric sensors in Earth Resource applications, the following conclusions were reached:

I. A more direct participation by Users in the planning and execution of exploratory measurements would enhance the immediate usefulness of the knowledge gained.

II. The low frequency region is essentially unexplored though physical reasoning in support of the benefits to be gained show that these potential benefits outweigh the attendant difficulties.

III. Instrumentation

(a) Though airborne measurement instrumentation is slightly more than a decade old, the results have demonstrated the ability to produce useful images. The passive microwave sensor is now at the transition stage - from infancy to maturity. Rapid technological progress can be anticipated with confidence. Advanced techniques have been identified and await development.

(b) The antenna size requirements for low frequency systems are incompatible with the capabilities of most present-day jet and piston type aircraft. Satellite systems, however, are capable of easily accommodating these antenna size requirements– even at the largest wavelengths in the low frequency region. The mechanical interface between the antenna structure and the aircraft observing platform is the prime deterrent to present day exploitation of the low frequency region.

(c) The complexity of present methods for obtaining Parametric Displays from aircraft observing platforms with the attendant laborious data reduction requirements and ineffective use of aircraft flight time has reduced this form of data display to minimal use, though it may be vital to the interpretation of imagery displays.

(d) Present aircraft imagery techniques are not optimum from a microwave radiometric standpoint. The use of antenna beam scanning degrades achievable sensitivity, restricts angular resolution, and establishes an unreasonable upper limit on aircraft velocities.

2.2 Recommendations

Sufficient information is available from the conclusions resulting from the study to make the following recommendations concerning a research and engineering program.

The objectives of a recommended research and engineering program are twofold:

(1) Development of the passive microwave instrument technology required to provide more effective methods for the accumulation and interpretation of observational data obtained from aircraft observing platforms.

(2) Application of the advanced techniques developed under Item (1) to the low frequency region to verify the efficacy of these new techniques and accelerate the exploitation of the benefits to be derived from data obtained at these low frequencies.

Research programs during the exploratory phase of Earth Resource applications, whether for the evaluation of advanced instrument developments or for the performance of measurements using available equipments, would benefit significantly through more direct participation by the User.

2.3 Comments in Support of Recommendations and Conclusions

Our concern with defining a useful contribution by microwave disciplines to the Earth Resource program effort was mentioned in the introductory remarks of the prior section. Differentiation was made between the usefulness of an approach devoted to an improved understanding of the physical processes associated with radiation from terrain materials versus other approaches which might lead more promptly to the identification of a useful application. A more direct User involvement in the exploratory program phase was suggested as an effective intermediary catalyst to optimize the usefulness of research discipline oriented contributions.

A brief discussion of these two features of the study presented in the form of a perspective over-view are included below.

Understanding vs. Useful

The use of passive microwave sensing for Earth Resource applications is in an exploratory phase. In its broadest sense the Earth Resource program is a study of the earth from remotely situated platforms in terms of the electromagnetic radiation emitted by, or reflected from, the earth at all wavelengths. In many wavelength ranges this has never been done, to any great degree, and so the value of such measurements and techniques remain to be demonstrated. This raises the question of how one can evaluate the potential of passive microwave data in Earth Resources applications. The inescapable conclusion is that there are many ways available to attack the problem and none can be singled out as "the" most appropriate. It might be argued that the only logical approach is to push forward with a thorough study of the interaction of microwaves with various materials. Such a study would include laboratory measurements throughout the entire microwave spectrum whereby the emission and reflection properties are established for various angles of incidence, polarization, and conditions of the particular material under investigation. This would be a fine scientific approach that might perhaps in ten years, permit one to know a great deal about the emissive and reflective properties of materials, but it is not intuitively obvious that the results would be of benefit to the Earth Resources Program. For example, could one predict, with a fair degree of certainty, the response to be expected from a glacial snow field, complete with wind blown areas of varying snow thickness overlying, in one instance, rocky material and, in another instance, frozen turf? Or, what differences can one expect in the microwave emission from heavily forested regions between summer and winter? Because of the nonhomogeneity of the earth, the scientific approach of "understanding" the microwave emission from individual materials is not directly applicable to the interpretation of Earth Resources data without a high degree of extrapolation which, by itself, introduces large uncertainties. Perhaps one might be able to argue that the scientific, laboratory approach could be conducted in such a manner that the results would be directly applicable, but the complexity of the problem seems to be so large that its solution is not on a reasonable time scale when viewed within the framework of the overall space effort. In the interests of expediency, it is appropriate to ask if other approaches are more beneficial.

At the other end of the scale, an approach which might be adopted is to build a system - or several systems to cover as many uncertainties as possible - and place it in earth orbit to learn what the properties of the signals are that must eventually be interpreted. Such an approach is not without its merits for it does face up to the complexities of the "real world". However, the experimenter in this case runs the risk of being criticized for not having a well thought out experiment with well-defined goals. Such criticism may, indeed, prove to be quite justified because the results of the experiment could be sufficiently difficult to interpret that no useful result would be forthcoming. However unlikely this may seem, it can not be ruled out.

Somewhere between the two extremes presented above there must be some approaches which optimize the benefits of the two methods and minimize the disadvantages. Here again, it is asking too much to expect to find one method of attack that is clearly superior to all others, but a reasonable approach would be some combination of the two extremes proceeding in parallel. For example, efforts to study the microwave properties of materials and to carry out observations on a grander scale could both proceed simultaneously. For these grander observations, it is of course eminently reasonable to consider aircraft, or helicopter platforms as means for evaluating the potentials of proposed systems without proceeding directly to the full-blown complexities of a satellite experiment. One consequence of such an approach, and by no means a trivial one, is the ability to schedule aircraft flights, or to stop the flights, when the interpretation of the data indicates such an extent that only a small fraction is ever interpreted, and then in only a superficial manner.

The philosophy presented above is that a sound, laboratory, approach to understanding the microwave interaction with materials is a notable goal in itself, but to be of value to the Earth Resource Program it should be coupled with field measurements, preferably performed from platforms which resemble, and attempt to duplicate as near as is practicable, the eventual operational system, be it satellites, aircraft, or helicopters.

Comments on User Requirements

During visits to many of the potential Users of passive microwave systems it became apparent that interest in the capability of passive microwave techniques was high, but areas of specific application were ill-defined and existing programs in microwave radiometry were in an early and exploratory phase. The reason for User interest appears to center on the ability of microwave radiation to penetrate clouds, haze, foliage, etc., and to respond to liquid water overlying other materials. To a lesser extent, User interest in microwave techniques is focused on the ability of the radiation to penetrate materials and provide information on subsurface phenomena, but a general uncertainty on the depth of penetration served to temper user interest.

In view of the above remarks it seems more appropriate therfore to concentrate on areas of User Applications rather than on User Requirements. A representative list of potential applications might include the following:

1) A determination of soil moisture content in forest areas as a means of evaluating the potential forest fire hazard in selected areas.
2) Determination of the relative soil moisture content among several areas fed by a common irrigation system in order that irrigation may be scheduled in the most efficient manner to provide maximum use of the available water.
3) Determination of the depth of the permafrost layer below the surface in arctic regions.
4) Map the distribution of surface water beneath large storms, such as hurricanes, to determine the nature and extent of disaster areas.
5) Determine relative ocean surface temperatures to map and observe the motion of thermal anomalies, such as the Gulf stream, and to correlate these with fish movements.
6) Determine the depth and water content of snow areas to schedule flood control and reservoir levels.
7) Determine the heat budget of glaciers to enable better prediction of water runoff therefrom.
8) Determine the line of demarcation between fresh and salt water to aid pollution studies.

The above list is far from complete, of course, but it does serve to illustrate how detailed some of the user applications might be and the wide range of problems to which microwave radiometric techniques might be applied. Of greater importance are certain common denominators which emerge from a listing of this sort. These are:

1) For any Earth Resource application, one wants to study the earth, independent of the atmosphere through which one looks, and there is only one wavelength region in the entire electromagnetic spectrum where that is possible, i.e. at wavelengths longer than $\sim$15 cm and less than $\sim$1m. All other wavelengths are seriously hampered by the ionosphere, liquid water in clouds, water vapor and oxygen in the atmosphere. These facts clearly predict maximum benefit to the User by making observations at wavelengths between 1 m and 15 cm.

2) Many of the User applications require the study of subsurface conditions and this can only be done at microwave wavelengths or longer. Furthermore, the depth of penetration is directly proportional to the wavelength, or nearly so, thereby enhancing the importance of studies made at wavelengths longer than 15 cm. Without use of these wavelengths, there is no hope of penetrating the surface to any significant degree.

3) Some of the user applications require the determination of a surface temperature, or a relative surface temperature, whereas others require a discrimination between different surface, or subsurface, materials. Very few user applications require a knowledge of the surface roughness, an obvious

exception being the value of sea state information to the oceanographer and the shipping industry. However, it is well known that the microwave emission from a rough surface is influenced by both the surface roughness and the temperature of the material, thus it is desirable to be able to either separate the two effects or to eliminate one of them. This again dictates long wavelengths to minimize the roughness effects on a scale smaller than a wavelength.

4) Another common denominator that is not obvious from a list of User applications reflects the use of other complementing types of data and the User's own preference for an all-encompassing visual display of his data. Most Users have long experience in looking at photographs or maps to gain the information they seek, and this has been carried over into the infrared sensors. It is very apparent that the User will respond more enthusiastically to microwave data if it can be presented to him in the form of a map, or image, which he can immediately compare to similar maps made in other wavelengths. Until this is realized and put into practice, microwave remote sensing will never play more than a minor role for many Users.

3.0 AREAS OF APPLICATION

In order to provide a foundation for this study, it was first necessary to determine what had been done in the past and where technology stands today. This was done by review of the published literature in this area beyond the work already carried out by Porter (1969), and by personal interviews with personnel at many of the Government Agencies involved in this program.

Of all of the resources utilized to generate this information, the major source was the NASA - ERC Earth Resource Surveys Office. Much of the needed information was readily available through the published references maintained by that Office. Additional information was also obtained through personal contacts with the various Government Agencies which are either supporting or carrying out efforts directly for the NASA.

The major emphasis in the NASA - Earth Resources Program is presently being placed upon those terrestrial resources for which the main economic and social benefits may accrue in the next ten years. The major application areas identified with the present Earth Resources Program are:

Oceanography and Marine Technology

Geology and Hydrology

Geography and Cartography

Agriculture and Forestry

In order to present the results of this survey in a concise manner, an outline format was adopted and applied to the information pertinent to each major application area. Starting with a listing of potential applications, each was reviewed in terms of the physical reasoning and analytical models which support the capability of the passive microwave sensor to meet application requirements. The results of supporting measurements were then reviewed and a comparison drawn where available between analytical models and experimental results. A brief summary of the conclusions derived from this information is included at the end of each section devoted to a major application area.

In the conduct of this study, an excellent starting point for the identification of potential areas of application proved to be the concise summary presented by P.C. Badgley and W.L. Vest at the Annual Meeting of American Society of Photogrammetry held on March 11, 1966, in Washington, D.C. The subject of this presentation was: "Unique Advantages of Orbital Remote Sensing for the Study of Natural Resources." Included in the presentation were five charts indicating the types of phenomena which might be "mapped" from space. The word "mapped" was defined to mean that certain natural and cultural phenomena are observed from space and recorded on photographs, images, tapes, or other data storage media.

The results of subsequent cost benefit studies to determine the feasibility and justification for a space-earth resource system have, in large, been based on the prognosis compiled by Badgley and Vest. Copies of the five charts from the Badgley, Vest report are included here as Figures 3-1 through 3-5, to serve as a reference base line.

ANTICIPATED OCEANOGRAPHIC APPLICATIONS OF REMOTE SENSORS

	SEA SURFACE THERMAL MAPPING	OCEAN WAVES	SHOALS & COASTAL MAPPING	CURRENTS	ICE SURVEILLANCE	COASTAL MARINE PROCESSES	BIOLOGICAL PHENOMENA	AIR/SEA INTERACTIONS	SEA LEVEL AND SEA SLOPE	WATER COLOR ANALYSIS	VOLCANIC ACTIVITY	SUBSURFACE STRUCTURE
1. METRIC CAMERA		X	X	X	X	X	X	X		X		
2. PANORAMIC CAMERA		X	X	X	X	X	X	X		X		
3. ULTRA-HIGH RES. CAMERA					X		X			X	X	
4. MULTIBAND SYNOPTIC CAMERA	X			X	X	X	X			X	X	
5. RADAR IMAGER		X	X		X	X	X	X				
6. RADAR SCATTEROMETER		X			X		X	X	X			
7. INFRARED IMAGER	X			X	X	X	X	X		X	X	
8. IR RADIOMETER/SPECTROMETER	X			X	X	X	X	X		X	X	
9. MICROWAVE IMAGER	X		X	X	X	X		X			X	
10. MICROWAVE RADIOMETER		X			X	X		X			X	
11. LASER ALTIMETER		X	X		X			X	X			
12. MAGNETOMETER												X
13. GRAVITY GRADIOMETER												X
14. ABSORPTION SPECTROSCOPY												
15. RADIO FREQUENCY REFLEC.												
16. VIEWFINDER			X		X	X	X	X		X	X	
17. TELEMETERING BUOYS	X	X		X				X	X			

Badgley & Vest (1966)

FIGURE 3-1

ANTICIPATED GEOLOGIC APPLICATIONS OF REMOTE SENSORS

COMPOSITION — STRUCTURE — STRATIGRAPHY SEDIMENTATION — MINERAL DEPOSITS — ENGINEERING — CRUSTAL — MANTLE STUDIES — OTHERS

	ROCK TYPES (GROSS)	LITHOLOGY	POROSITY	PERMEABILITY	FABRIC (GROSS)	FAULTS, FOLDS	SALT DOMES	CORAL REEFS	RIVER SEDIMENTS	NEAR SHORE & BEACH DEPOSITS	DUNES	STREAM, LAKE, BAY DEPOSITS, FANS	FAULTS, FOLDS	ALTERATION, CONTACT ZONES	INTRUSIVE ROCKS	METALLOGENIC PROVINCES	OIL SHALE	SURFACE ROUGHNESS	SOIL MOISTURE DIST.	PERMAFROST	SLOPE STABILITY	COMPACTION	EARTHQUAKE ZONES	VOLCANOES, THERMAL WATERS	HEAT BALANCE, VARIATIONS	MAGNETIC FIELDS	GRAVITY GRADIENTS	INTERNAL CONSTITUTION	ISOSTASY	CONTINENTAL DRIFT	GLACIATION (CONTINENTAL, VALLEYS)	
1. METRIC CAMERA	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	X	
2. PANORAMIC CAMERA	X	X		X	X	X	X	X	X		X	X	X			X	X	X					X	X	X					X	X	
3. ULTRA-HIGH RES. CAMERA	X	X	X	X		X	X		X	X			X	X	X	X	X	X			X	X	X	X	X						X	
4. MULTIBAND SYNOPTIC CAMERA	X	X	X	X	X	X	X	X	X		X	X			X	X	X	X				X	X	X	X						X	
5. RADAR IMAGER	X		X	X	X	X	X			X	X	X	X		X	X		X				X										
6. RADAR SCATTEROMETER	?			?												X		X				X										
7. INFRARED IMAGER	X		X	X	X	X	X	X	X	X	X	X	X	X		X	X		X	X				X	X			X				
8. IR RADIOMETER/SPECTROMETER	X	X	X					X	X		X	X			X	X	X		X	X				X	X			X				
9. MICROWAVE IMAGER	X				X			X	X		X	?						?	?	?					X						X	
10. MICROWAVE RADIOMETER	?	?	X	X							X							?	?	?					X						X	
11. LASER ALTIMETER						X	X	X					X			X		X											X	X	X	
12. MAGNETOMETER															X	X										X		X	X	X		
13. GRAVITY GRADIOMETER						?									X												X	X	X	X		
14. ABSORPTION SPECTROSCOPY		X																X	X			X										
15. RADIO FREQUENCY REFLEC.	?																														X	
16. ULTRAVIOLET	X	X	?	?		?	?	X	X	X	X	X	?	X	X	X	X					X			?							
17. VIEW FINDER								X	X			X												X							X	

Badgley & Vest (1966)

FIGURE 3-2

ANTICIPATED HYDROLOGIC APPLICATIONS OF REMOTE SENSORS

	EVAPOTRANSPIRATION	WATER SURFACE ROUGHNESS	RAIN DISTRIBUTION AND INFILTRATION	GROUND WATER DISCHARGE	IDENTIFICATION OF SUB-AQUEOUS FEATURES	SALT CONTENT AND LIGHT ABSORPTION OF WATER	WATER POLLUTION	RESERVOIR SEDIMENTATION	EFFLUENTS OF MAJOR RIVERS	RUNOFF & WATER RETENTION IN GLACIERS	WATER REGIMEN OF VALLEY GLACIERS	MONITORING OF LAKE AND RESERVOIR LEVELS	SNOW SURVEYING	EROSION & SEDIMENTATION RATES
1. METRIC CAMERA		X	X		X			X		X	X		X	X
2. PANORAMIC CAMERA			X	X	X		X	X	X	X	X	X	X	X
3. ULTRA-HIGH RES. CAMERA		X	X	X	X	X	X	X	X	X	X	X	X	X
4. MULTIBAND SYNOPTIC CAMERA	X		X	X	X	X	X	X	X	X				X
5. RADAR IMAGER	X		X	X			X		X	X			X	X
6. RADAR SCATTEROMETER			X							X			X	
7. INFRARED IMAGER	X		X	X			X		X	X	X		X	
8. IR RADIOMETER/SPECTROMETER	X	X					X			X	X		X	
9. MICROWAVE IMAGER			X	X			X			X	X		X	X
10. MICROWAVE RADIOMETER	X		X				X			X	X		X	
11. LASER ALTIMETER												X		
12. MAGNETOMETER														
13. GRAVITY GRADIOMETER														
14. ABSORPTION SPECTROSCOPY														
15. RADIO FREQUENCY REFLEC.	X		X							X				
16. VIEWFINDER			X				X					X		
17. TELEMETERING BUOYS														

Badgley & Vest (1966)

FIGURE 3-3

ANTICIPATED GEOGRAPHIC APPLICATIONS OF REMOTE SENSORS

	LAND USE	URBAN STUDIES	TRANSPORTATION AND LINKAGES	SETTLE & POPULA. MOVEMENTS	RESOURCES UTILIZATION	VEGETATION COVER & SOILS	CLIMATIC CONDITIONS	ENERGY BUDGET (INC. WATER)	GEOMORPHOLOGY	GLACIOLOGY AND PERMAFROST	TOPOGRAPHIC & THEMATIC MAP.
1. METRIC CAMERA	X	X	X	X	X	X	X	X	X	X	X
2. PANORAMIC CAMERA	X	X	X	X	X	X	X	X	X	X	X
3. ULTRA-HIGH RES. CAMERA	X	X	X	X	X	X			X		X
4. MULTIBAND SYNOPTIC CAMERA	X	X	X	X	X	X	X	X	X	X	X
5. RADAR IMAGER	X	X	X		X		?		X	X	X
6. RADAR SCATTEROMETER		?	?								
7. INFRARED IMAGER	X	X	X								
8. IR RADIOMETER/SPECTROMETER	X	X	X								
9. MICROWAVE IMAGER	X	X	?			X				X	
10. MICROWAVE RADIOMETER		?	?								
11. LASER ALTIMETER											X
12. MAGNETOMETER					X						
13. GRAVITY GRADIOMETER											
14. ABSCRPTION SPECTROSCOPY											
15. RADIO FREQUENCY REFLEC.											
16. VIEWFINDER			X		X		X				X

Badgley & Vest (1966)

FIGURE 3-4

ANTICIPATED AGRICULTURE AND FORESTRY APPLICATIONS OF REMOTE SENSORS

	TOPOGRAPHY	TIMBERLINE	WATERLINE	SNOWLINE	DESERTLINE	GRASSLAND-BRUSHLAND INTERFACE	BRUSHLAND-TIMBERLAND INTERFACE	GRASSLAND-TIMBERLAND INTERFACE	SOIL SERIES	VEGETATION DENSITY	TREE COUNT AND IDENTIFICATION	TREE CROWN DIAMETER	CROP SPECIES	IRRIGATION WATER (SNOW PACK)	STRESS (DISEASE) EVAPOTRANSPIRATION	PLANT VIGOR	FIELDS, LESS THAN ONE ACRE	FIELDS, ONE TO TEN ACRES	FIELDS, GREATER THAN TEN ACRES	SOIL MOISTURE	SOIL TEMPERATURE	FIRE DETECTION (PREDICTION)	DAMAGE ASSESSMENT (FLOODS)	LIVESTOCK CENSUS (ECOLOGY)
1. METRIC MAPPING CAMERA	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X
2. PANORAMIC CAMERA	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X
3. ULTRA-HIGH RES. CAMERA	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X			X	X
4. MULTIBAND SYNOPTIC CAMERA	X	X	X	X	X	X	X	X		X				X			X	X	X				X	X
5. LASER ALTIMETER	X																							
6. RADAR IMAGER	X	X	X	X	X	X	X	X	X	X				X			X					X	X	
7. OPTICAL-MECHANICAL SCANNER (.32 - 16.0 MICRONS)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
8. INFRARED RADIOMETER		X	X	X						X			X		X		X	X	X	X	X	X	X	
9. MICROWAVE IMAGER	X													X						X			X	
10. MICROWAVE RADIOMETER	X													X						X	X	X	X	
11. VIEW FINDER																						X	X	
ON THE GROUND 12. THERMOMETER AND HYDROMETER															X					X	X			
13. ANEMOMETER															X							X	X	
14. WEIR STREAM GAUGE														X									X	
15. FATHOMETER														X									X	
16. SNOW PACK INTEGRATOR														X										
17. XEROMETER																						X		
18. PARTICLE SIZE ANALYZER														X	X									

Badgley & Vest (1966)

FIGURE 3-5

3.1 Oceanography and Marine Technology

The ocean is an integral part of our environmental and socio-economic system. Users of space-acquired oceanographic data may be grouped according to the following fields of interest:

- Fisheries
- Shipping
- Coastal Mapping
- Marine Meteorology
- Forecasting of Ocean Phenomena for improved utilization of equipment and greater safety of personnel and equipment

There has been a significant increase in marine environment activities in the last two decades. Exploitation of the food resources of the sea, oil extraction from the continental shelf, and off-shore mining activities are just a few marine related activities. The requirements for oceanographic data are as diverse as the individual activities of interest. To provide a comprehensive view of the potential applications and associated requirements, reports from the following organizations were reviewed:

- NASA
- Space Oceanography Project (NAVOCEANO)
- National Academy of Sciences
- Department of Commerce
- Department of Interior

Applications

The following list of potential applications of passive microwave radiometric sensors to oceanography (see Figure 3-1) were examined:

- Sea Surface Thermal Mapping
- Ocean Wave Structure
- Shoals and Coastal Mapping
- Currents
- Ice Surveillance

Coastal Marine Processes
Air/Sea Interactions
Volcanic Activity

Models

Oceanography has been the beneficiary of more analytical model studies than any other major area of application insofar as microwave radiometry is concerned. The proliferation of model studies applied to oceanography might imply that a more intense effort has been devoted to applications in this area in anticipation of a higher level of immediate benefit to potential Users. This is not the case at all. The reason is simply that analytical models can be more easily developed in terms of a semi-infinite homogeneous medium typical of the ocean, than for materials which require consideration of complex stratified layers with varying spatial distributions. The conducting properties of the ocean limit the depth of penetration to a fraction of a wavelength. This allows a considerable simplification in comparison with applications involving dry soil where the depth of penetration may be several wavelengths. These factors determine the radiation from the material's surface.

Energy reflected from the surface is superimposed on the radiated energy. The magnitude of the reflected component is determined by the surface reflectivity and the intensity of the flux incident on the surface. In the microwave region, the prime source of incident flux is the atmosphere.

A radiometric sensor located above the surface observes both components of radiation — one radiating from the surface, and the other reflected from the surface. The composite radiation is attenuated by the atmosphere before reaching the sensor antenna. Radiation directly from the atmosphere outward, toward the sensor, is also sensed by the radiometer.

Thus, the three major components of radiation received by an airborne or spaceborne radiometer, which must be considered in the development of an analytical model, independent of the application are: the outgoing radiation from the material itself, the reflected radiation from the surface of the material, and the outward radiation from and attenuation by the atmosphere.

Analytical models for specific applications are primarily concerned with the electrical properties of the material and the geometrical properties of the surface boundary with the atmosphere, since these parameters determine the direct and reflected radiation characteristics of the material. Atmospheric attenuation and radiation characteristics must also be considered in deriving a complete model. A common approach is to consider that the atmosphere may be represented in uniform horizontally stratified layers. Though this is known to be an over-simplified assumption, a more rigorous treatment awaits improvement in present knowledge concerning the spatial and frequency dependent radio characteristics of the atmosphere. One can draw the conclusion, however, that the use of these simplifying assumptions concerning the radio properties of the atmosphere are far more critical in predicting or interpreting observed microwave radiation at short wavelengths than at long wavelengths - with the transition between short and long near a wavelength of 6 cm.

The physics of microwave remote sensing of terrain materials has been described by several investigators. The contributions by Peake and others on the staff at Ohio State University are among the more notable. A comprehensive summary of these fundamental considerations, prepared by D.H. Staelin, is included as an Appendix to this report.

These general principles have been applied to a variety of remote sensing applications. The most notable analytical models associated with oceanography are those developed by Peake, Stogryn, and Sirounian.

An excellent review of these analytical models has recently been presented by Paris (1969) in which he extends these model predictions over a much broader frequency range than the original authors. Paris also introduces a more realistic dynamic range of atmospheric effects, leading to the identification of the sky noise component as a critical parameter in short wavelength observations.

In the Stogryn model, it is assumed that the atmospheric contribution to apparent "brightness" temperature results from horizontally stratified layers containing no rain, clouds, fog, or hail. The associated atmospheric attenuation and radiation is due solely to water vapor and molecular oxygen.

In the Stogryn development, the radii of curvature of the wave structure are considered large, compared to the wavelength of observation. Following the development of Peake, the utilization of the reciprocity properties of differential scattering coefficients leads to the derivation of Kirchhoff's radiation law in its most general form accommodating both the angular dependence and polarization properties of the emitted radiation. The scattering coefficient of the surface is defined by Stogryn in terms of its relationship with the albedo of the surface (ratio of scattered to total power incident on a surface from a particular direction and at a specific polarization and frequency).

In order to introduce the polarization properties of the radiation, the usual von Fragstein (1955) statement of the Kirchhoff law is altered, while maintaining the black body assumption, leading to the conclusion that horizontally and vertically polarized emissivity equals horizontally and vertically polarized absorptivity, respectively. From this generalized Kirchhoff radiation law, a knowledge of the scattering coefficients yields the emission coefficient.

Since the usual formulas for infinitely conducting normally distributed surfaces with large radii of curvature are not applicable to radiometric problems (thermal emission coefficients go to zero), Stogryn introduces a finite (complex) dielectric constant for sea water to facilitate the derivation of a scattering coefficient which is consistent with the Kirchhoff approximation. For a rough surface, it is consequently shown that the scattering coefficient is a function of the mean-square wave slope.

The necessary statistics (including mean-square wave slope) are introduced (Cox and Munk) by means of the experimental determination that the slope distribution of the sea surface is nearly Gaussian. The wave slopes are given directly in terms of wind velocity. Corrections for skewness and peakedness, given by Cox and Munk, are assumed by Stogryn to be negligible.

Stogryn's results are presented for various wind conditions. The highlights are;

(i) For horizontally polarized radiation, large "signal" temperature variations are observed with increasing wind speed (the largest variations occurring at $\Theta \simeq 50°$).

(2) For vertically polarized radiation, the "signal" temperature is much less affected, and at a look angle of 50° (at 19.4 GHz) is almost independent of the state of the sea.

Stogryn concludes that it would be more appropriate to sense vertically polarized radiation (preferably at $\Theta \simeq 50^{\circ}$) for sea surface temperature determinations, and horizontally polarized radiation for sensing of surface roughness conditions.

It is instructive to list the assumptions made by Stogryn.

(1) The Kirchhoff approximation is assumed to be valid at 19.4 GHz.

(2) The slope distribution of the sea surface is assumed to be Gaussian. Skewness and peakedness are neglected.

(3) The effects of rain and cloud attenuation and radiation are not included.

(4) Spatial variations in water vapor content are considered negligible.

(5) The temperature of the ocean at and below surface is considered to be uniform.

(6) The model may be restricted due to the fact that the Cox and Munk data does not include winds in excess of 28 knots.

The Sirounian model statistically examines the problem of reflection and emission of microwave radiation from the rough sea. An analytical solution at 1.6 cm allows for a detailed comparison with the model of Stogryn. Introduction of the Stokes parameters by Sirounian allows information, in addition to the two components of polarized intensity, to be obtained concerning the degree of polarization and the position of the plane of polarization. The dependence of the latter two quantities upon sea surface roughness is extensively examined. In determining the characteristics of the reflected radiation from the sea surface, the radiation reflected from the n^{th} slope is integrated over the probability function representing the statistical distribution of sea slopes.

Sirounian assumes, as does Stogryn, the validity of the Cox and Munk experimental dependence of the statistical distribution of the sea slope upon wind speed. The distribution was found to be represented by a Gaussian function with refinements introduced by a Gram - Charlier type series (See Cox and Munk, 1954). Stogryn, however, neglected the Gram - Charlier skewness and peakedness correction.

In the Sirounian development, reflection matrices are formulated for the n^{th} slope of a rough sea in terms of the Stokes parameters. Employing the Rayleigh Jean approximation, intensities are found to be proportional to the temperature of the emitter. Brightness temperature is defined as the product of emissivity and thermometric temperature. On the basis of statistical average, there are more waves with small slopes than waves with large slopes (Cox and Munk). Thus, a large portion of the incident radiation is reflected according to Fresnel reflection at an angle equal to the angle of incidence. The principle of reciprocity is applied in a manner such that the reflected and emitted radiation in the original direction of incidence, under thermodynamic equilibrium, is equal to the incident flux. Thus, the emitted radiation is determined by subtracting the total reflected radiation in all directions from the incident electromagnetic radiation.

Several significant numerical results are listed by Sirounian for the analytical case corresponding to a wavelength of 1.6 cm. It is important to note, however, that Sirounian has defined horizontal and vertical polarization in a manner opposite to that of Stogryn. (That is, vertically polarized radiation is defined by Stogryn as that component whose electric vector lies in the plane of incidence). Comparison of the two models (Sirounian and Stogryn) entails no more than an interchange of the words "vertical" and "horizontal" when referring to polarized components in the Sirounian treatment.

Significant conclusions derived from the Sirounian development and interpreted in this manner include:

(a) Changes of the vertically polarized brightness temperature with ocean roughness are smaller than observed in the horizontal component and are proportional to surface roughness at small look angles ($< 25°$), but inversely proportional at large angles ($> 50°$). The variations are larger at large angles of observation. Variations in the vertically polarized brightness temperature component with ocean roughness are negligible at look angles between 30° and 50° referenced to nadir.

(b) Variations of the horizontally polarized brightness temperature with surface roughness are predicted to be the reverse of the vertically polarized component. Negligible variations in the horizontally polarized component of brightness temperature are found between look angles of 20° to 40°. Large variations are predicted for large angles of observation.

(c) At a 60° angle of observation, variation in the anticipated brightness temperature with ocean roughness are of order 7° to 8°K for a 5m/sec. change in wind velocity.

In addition to the polarization intensity results, the Sirounian model predicts that the degree of polarization will be affected by sea state. In particular:

(d) The magnitude of polarization will increase at small angles of observation and decrease at large angles of observation as the ocean roughness increases.

(e) The change of the degree of polarization will be greatest at large angles of observation (50° to 70°).

The Sirounian model also predicts that the position of the plane of polarization will;

(f) Change with ocean roughness (about 2.5° for each 5 m/sec. change in wind velocity, at a look angle of 60°).

(g) Increase with ocean roughness at angles of observation greater than 10°.

(h) Decrease with ocean roughness at small angles of observations (less than 10°).

Finally, the Sirounian model indicates that the wind direction may be significant, i.e.,

(i) At large nadir angles of observation, both polarized components of brightness temperature, in addition to their degree of polarization will increase slightly when the wind direction approaches the direction of observation.

(j) For a wind normal to the direction of observation, wind speed dependent variations will occur in the plane of polarization (particularly at a look angle of 60°).

There is significant disagreement between the models (Sirounian and Stogryn) concerning the variation of brightness temperature with sea surface roughness at any particular angle of observation. At an observing frequency of 19.4 GHz, we can make the following comparison.

Stogryn	Sirounian
Vertically polarized radiation increases with surface roughness for $\Theta < 50°$ but decreases for $\Theta > 50°$.	Similar prediction
At $\Theta = 50°$, the vertically polarized component is found to be independent of the state of the sea.	Invariance occurs at $\Theta \simeq 40°$.
Vertically polarized temperatures appear to approach infinity at $\Theta \sim 90°$ (no Gram-Charlier corrections were made).	Similar prediction, even though Gram-Charlier corrections were incorporated.

Horizontally polarized radiation increases with surface roughness for $\Theta < 75°$.	Here, Sirounian's model significantly differs from that of Stogryn. An increase is found for $\Theta > 40°$, but a decrease for $\Theta < 40°$.
There is no angle at which horizontally polarized radiation is found to be independent of the state of the sea.	Invariance occurs at $\Theta \simeq 35°$.
Largest variations in the horizontal component as a function of wind speed occur at $\Theta \simeq 50°$.	Largest variations occur at very large angles, that is, $\Theta \rightarrow 90°$.
The changes in both vertically and horizontally polarized radiation with wind speed for a fixed look angle are larger for $\Theta > 50°$ than for small angles of observation.	Similar prediction
Very slight variations are found for the horizontally and vertically polarized components as a function of wind direction. For	A vaguely similar phenomenon occurs...also, crosswind and upwind variations affect the plane of

$\Theta < 50°$, the upwind case appears to produce larger brightness temperatures.	polarization

The previously mentioned reports by Paris, (1969,) and Porter, (1969,) provide comprehensive reviews of theoretical models as well as measurements. The Paris report is concerned with the application of microwave radiometry to marine meteorology and oceanography. The Porter report provides a broad view of several fundamental considerations which are interpreted quantitatively for a variety of applications.

Paris lists the several factors which determine the intensity field of microwave radiation as observed from the vantage point of aircraft or satellite vehicles in two groups: environmental and geometrical. These include:

- Environmental Factors
  - Atmospheric Factors
    - The distribution of temperature, pressure water vapor, and liquid water.
    - The distribution of rain drops, sizes.
    - The intensity of cosmic radiation.
  - Oceanographic Factors
    - The temperature and salinity of the surface layer of the ocean.
    - Sea Foam
    - Bubbles
    - Surface Roughness
- Geometrical Factors
  - Frequency of Microwave Radiation
  - Polarization
  - Incidence Angle

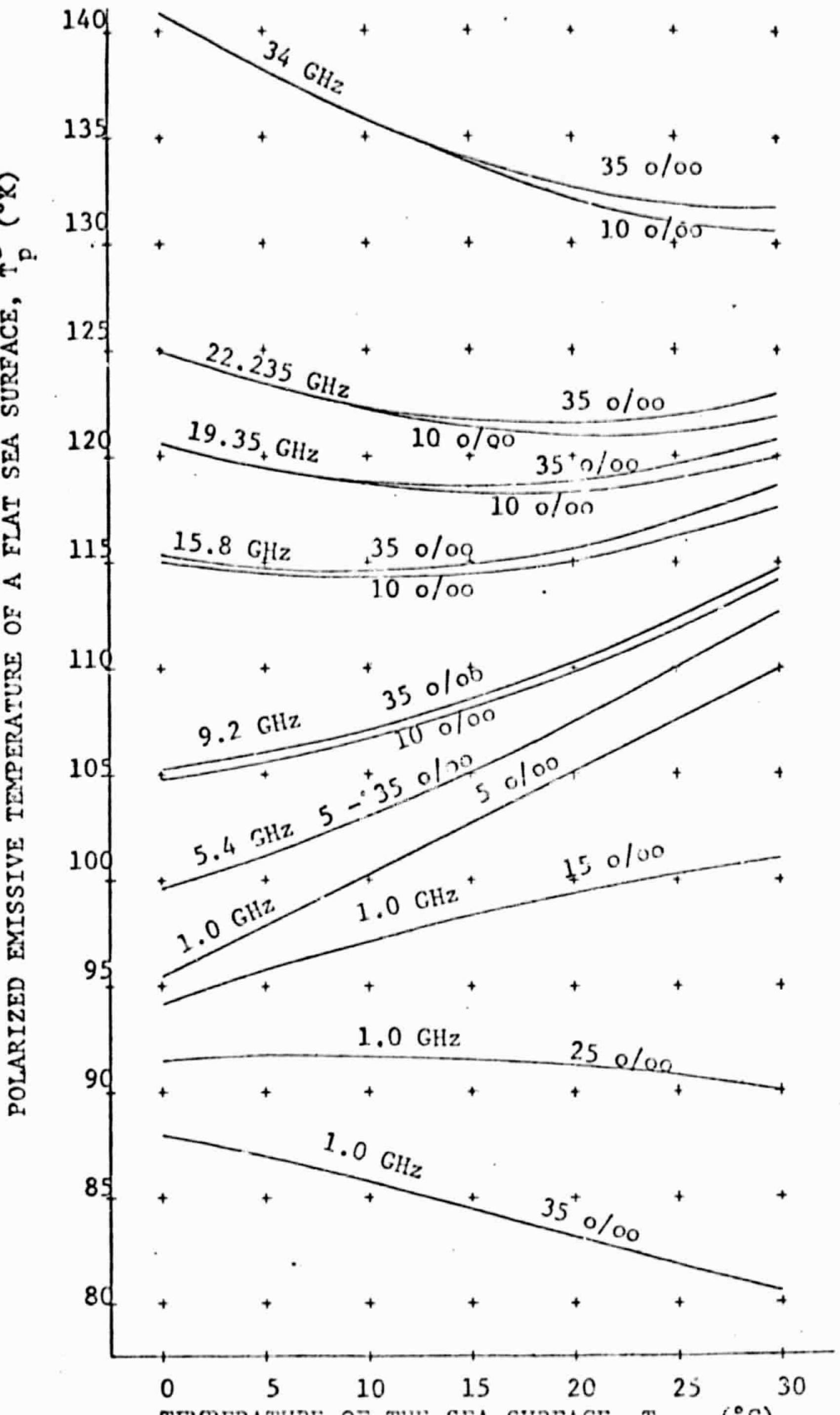
Paris computed the complex dielectric constant of sea water as a function of temperature, salinity, and frequency. Using Fresnel's law of reflection for flat sea surfaces, he computed the apparent black body temperature of the polarized emission from the sea's surface for various combinations of temperature, salinity, and frequency. His results are shown in Figure 3-6. The important features are the prediction that the polarized emissive temperature of sea water is almost constant with temperature and salinity for frequencies near 15 GHz. It is linearly proportional to temperature for frequencies near 5.4 GHz, and is strongly dependent upon temperature and salinity for frequencies less than 4 GHz. He further notes that the presence of foam on the sea surface, due to high sheering stresses present in rough seas may cause a significant increase in the emissivity of the sea surface for all microwave frequencies. An analytical model is not developed; however, it is suggested that heavy seas or precipitation may negate the model predictions of Sirounian and Stogryn.

Paris expresses concern with the Kreiss (1968) model for the polarized brightness of up-welling microwave radiation over various types of clouds, in regard to the Kreiss assumption that the sea surface acts as a smooth flat surface, even under rain and clouds. Rain falling on the sea surface would create bubbles and foam which would tend to raise the apparent radiance of a cloud at microwave frequencies, as a consequence of the associated increase in the flux component emitted by the sea underneath a cloud.

Measurements

A limited number of measurements have been performed which have a direct bearing on oceanographic applications of passive microwave sensing. Ground based measurements have been reported by several researchers; see Peake, Porter, and Edgerton. Aircraft measurements have been reported by Capurro (1969), Nordberg, et al (1969), and by Singer and Williams (1968).

The earth based measurements reported by Edgerton are particularly relevant to the comments of Paris and Williams concerning the significance of foam, air bubbles, and rain



The polarized emissive temperature of a flat sea surface versus the thermometric temperature of the sea surface for frequencies of 1, 5.4, 9.2, 15.8, 19.35, 22.235, and 34 GHz and for various salinities.

(Paris 1969)

FIGURE 3-6

on the surface of the ocean. Using a mobile van installation, field measurements were performed at Ventura Marina, Marineland of the Pacific, and on the Balboa pier at Newport Beach, California. The purpose of these measurements was to obtain a basic understanding of the microwave emission characteristics of the littoral zone and the near-shore ocean environment. Measurements of the littoral zone were conducted to establish the microwave characteristics of breakers, foaming water, spray, the swash zone, etc. These experiments included stationary measurements taken from a pier while viewing selected areas of the littoral zone, and continuous measurements of microwave profiles taken while the mobile van was moved slowly outward from the shore line along the pier. These measurements indicated a marked variation in the observed microwave brightness temperature due to varying ocean surface conditions. The measured vertically and horizontally polarized 37 GHz microwave temperatures obtained during an antenna beam traverse across the relatively dry beach sand and out into the near shore environment are shown in Figure 3-7. For these measurements, the antenna was pointed at a 50° nadir angle. The projected field of view on the ocean's surface was approximately 7 ft. x 4.5 ft. The dynamic range of observed brightness temperatures at each polarization are contained within the two curves shown for each polarization. A significant feature of the data is the very warm microwave temperature of the foam in the breaker region.

Edgerton concluded as a result of these measurements that the high emissivity associated with foaming water should be introduced in analytical models, such as those of Sirounian and Stogryn, in order to provide a more realistic model.

Several measurements were also made by Edgerton of the open ocean beyond the breaker zone for various antenna viewing angles in order to establish the relationship between microwave brightness temperature and sea state conditions. These measurements are summarized in Figure 3-8. The average vertical polarization brightness temperature versus average horizontal polarization brightness temperature are shown in this figure for various near-shore sea states. Brightness temperatures of the surf zone are also shown in this figure. It is of interest to note that the 13.4 GHz temperatures tend to be warmer for the higher sea states in agree-

TRAVERSE OF BEACH SHOWING MAXIMUM AND MINIMUM VERTICAL AND HORIZONTAL POLARIZATION BRIGHTNESS TEMPERATURES FOR VARIOUS NEAR SHORE SEA STATES

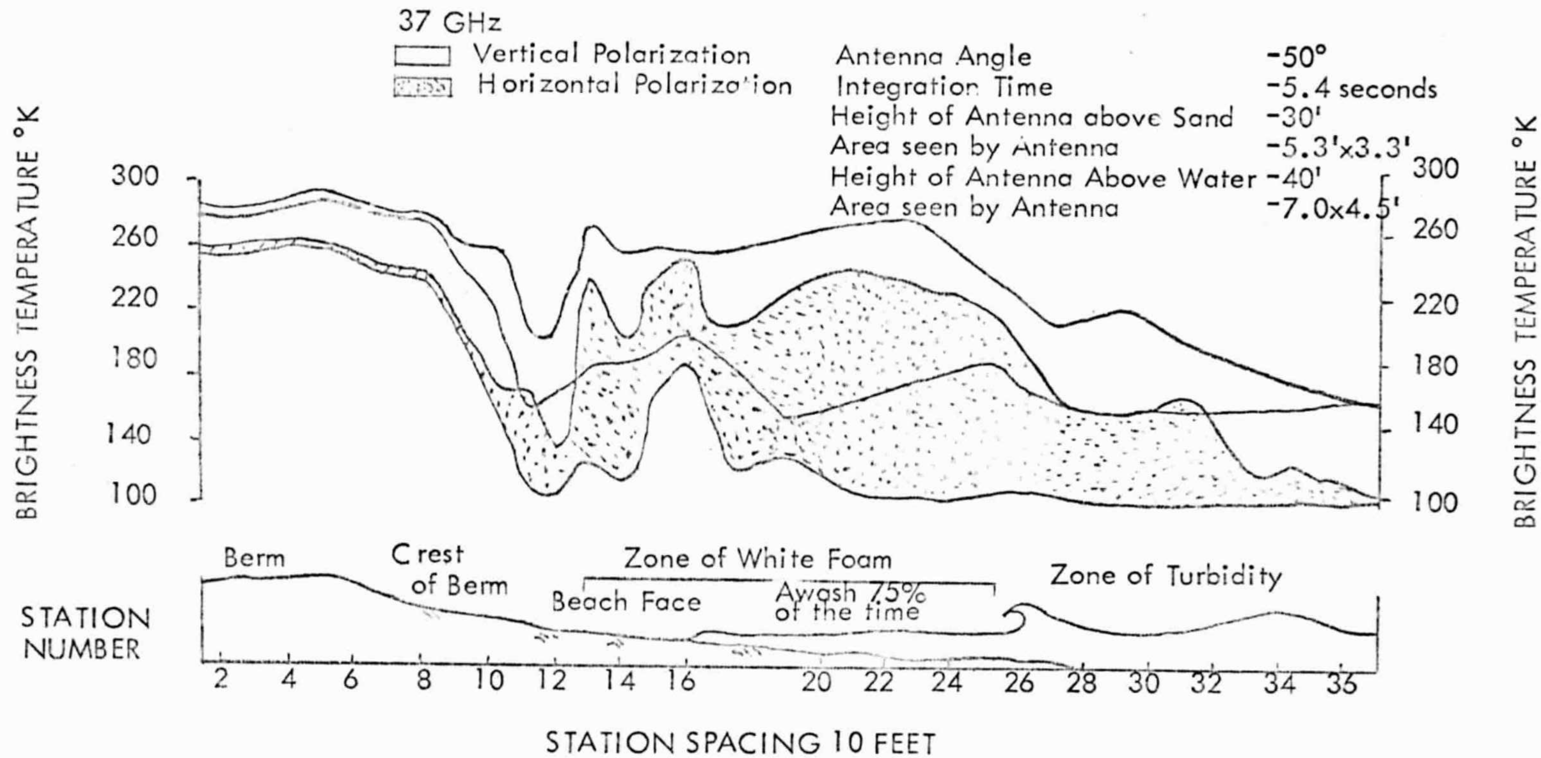


FIGURE 3-7 (Edgerton, 1968)

AVERAGE VERTICAL POLARIZATION BRIGHTNESS TEMPERATURE VS.
AVERAGE HORIZONTAL POLARIZATION BRIGHTNESS TEMPERATURE
FOR VARIOUS NEAR SHORE SEA STATES

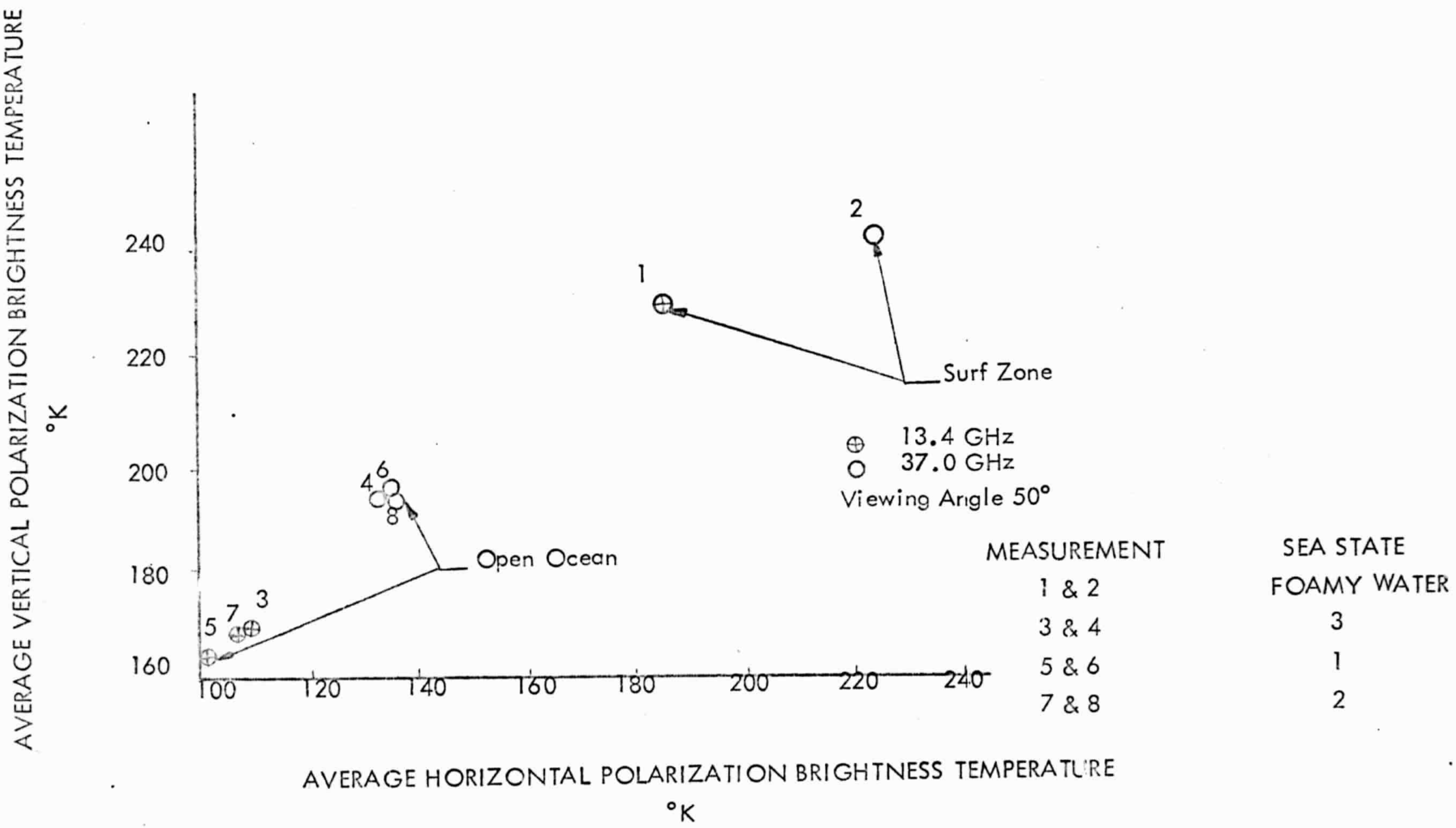


FIGURE 3-8 (Edgerton, 1968)

ment with the analytical models developed by Stogryn and Sirounian. The 37 GHz temperatures, however, do not coincide with the analytical models.

Few measurements have been made of the microwave radiation over the ocean under conditions in which the distributions of essential atmospheric and hydrospheric parameters were adequately known. Most of the reported measurements have been performed using an instrumented Convair 240A, designated as NASA 926, which is operated by the Manned Spacecraft Center, and a Convair 990 used by the Goddard Space Flight Center.

Blinn (1967) has described the microwave radiometers installed in the Convair 240A. There are two separate microwave radiometers installed on this aircraft, designated the MR-62 and the MR-64. The MR-62 operates at 15.8 GHz and 22.235 GHz using a common antenna. The MR-64 operates at 9.2 GHz and 34 GHz, again using a common antenna. The antenna feed systems for the MR-62 are cross-polarized. The feed systems for the MR-64 are polarized in the same plane. Mechanical rotation of the antenna systems through 90° about their boresight axis is required in order to change the polarization planes. The antennas are mounted in the nose of the NASA 926 aircraft which allows look angles of observation from 0 to 45°. The look angle, like the polarization angle can be mechanically adjusted.

Observational data accumulated over the Gulf of Mexico during the mid and latter part of 1967, with the MR-62 and MR-64 radiometers, is discussed in detail by Paris (1969).

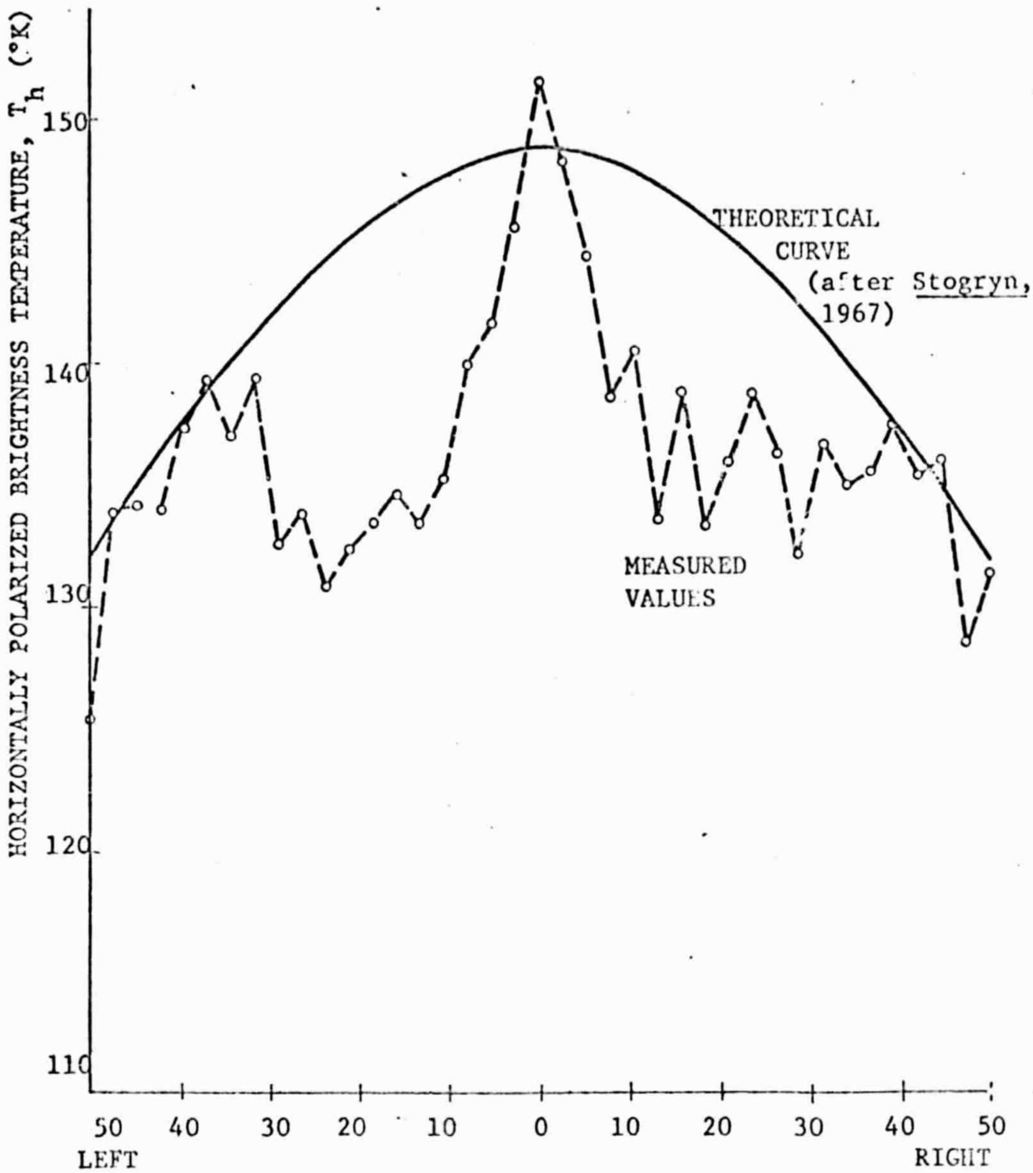
The microwave radiometer installed in the Convair 990 was developed by the Goddard Space Flight Center. The antenna beam is electronically scanned. The operating frequency is 19.35 GHz. The antenna consists of an 18" by 18" array of dipoles in which the phase relationship between respective dipoles is controlled in a manner which allows formation of a highly directive antenna beam that can be step-scanned normal to the aircraft ground track ± 50° from the nadir.

Measurements performed with this system over the Gulf of Mexico during June 1967 were of particular significance since the observational data allowed direct comparison with the Sirounian and Stogryn theoretical models. A graphical plot of the observational data obtained by this radiometer in a flight over the central western Gulf of Mexico on June 5, 1967, is shown in Figure 3-9. The flight altitude was approximately 10 km. Reports from surface ships reported a sea temperature of approximately 18°C. The estimated salinity was 36.5 grams solute per kilogram of solution (°/oo).

The environmental conditions based on photographs taken from the Convair 990 during the flight indicated that the sky was practically clear and that the ocean surface was quite smooth. The solid-line in Figure 3-9 is the theoretical distribution of horizontally polarized brightness temperature with incident angle, based on the Stogryn model for a flat sea surface. As shown in Figure 3-9, the measured and predicted temperatures agree at look angles near nadir and ±50°. There appears to be some disagreement for values near ±20°. Paris (1969) suggests that the discrepancy at this look angle may be due to antenna effects.

During the flight on June 5, 1967, (identified as Flight 12), the ground track of the aircraft passed over the coast of Texas near Houston. A plot of the observed brightness temperature versus time is shown in Figure 3-10. Of interest is the large increase in brightness temperature when one goes from water to land. The inter-coastal canal, bordered on the Gulf side by a narrow strip of land, is also easily distinguishable.

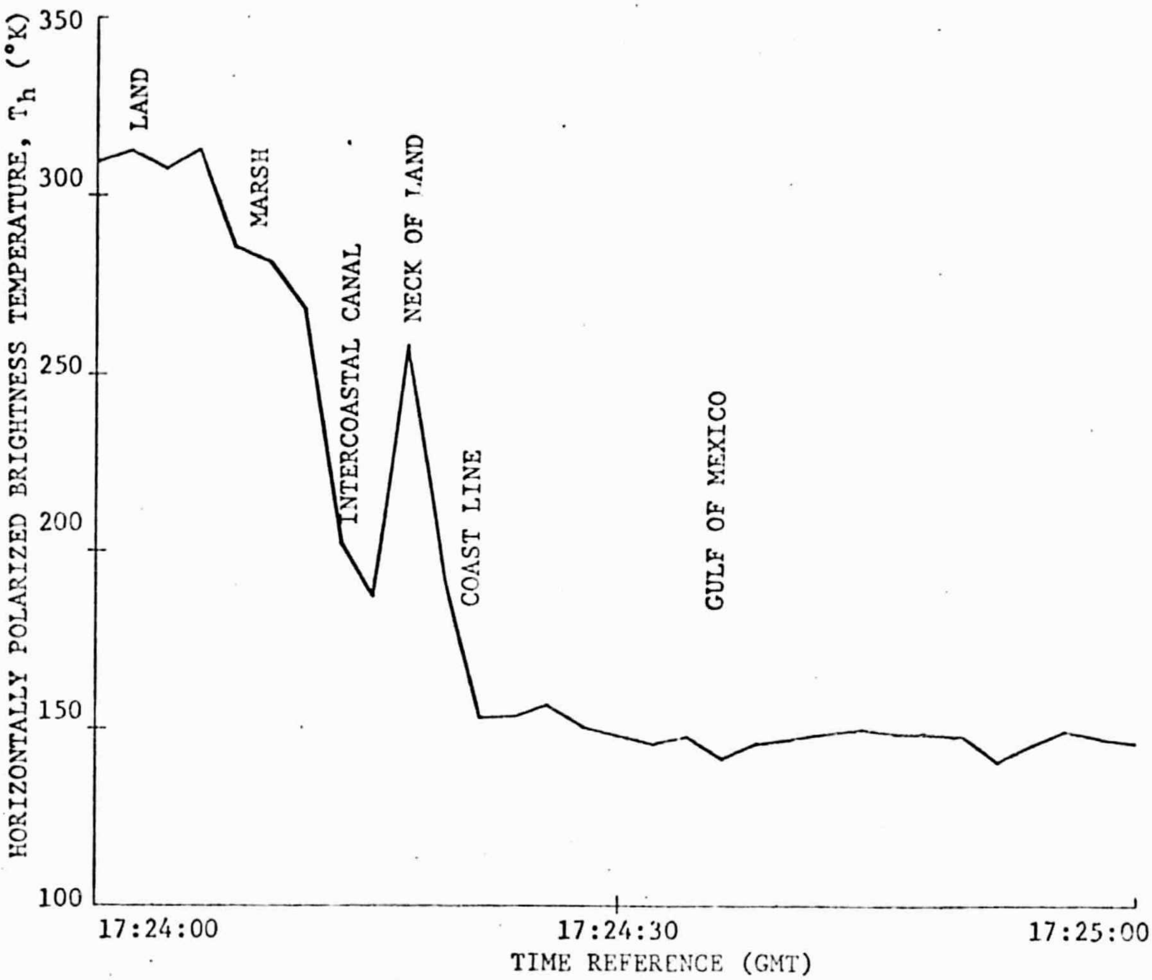
On the following day, June 6, 1967, the Convair 990 was flown over various types of clouds present in the Gulf of Mexico. One portion of this flight (Flight 13) passed directly over a small group of cumulus clouds. The observed brightness temperature as a function of time along the ground track is shown in Figure 3-11. Measured values are shown as circles. A smooth analysis of the data is indicated by the solid line. It is apparent from these measurements that a significant increase in brightness temperature is observed when the antenna is pointing directly down over the core of the cloud. Paris suggests that this pronounced increase may occur over those portions of the cloud which may contain water droplets large enough and dense enough to fall as rain. Visual observations during this flight indicated that the cloud top was at an altitude of approximately 4.6 km, and the cloud base



The average value of the horizontally polarized brightness temperature (circles and dashed line) measured during Flight 12 from 18:13:00Z to 18:13:30Z versus incidence angle and corresponding theoretical values (solid line) from Stogryn (1967) for a frequency of 19.35 GHz.

(Paris 1969)

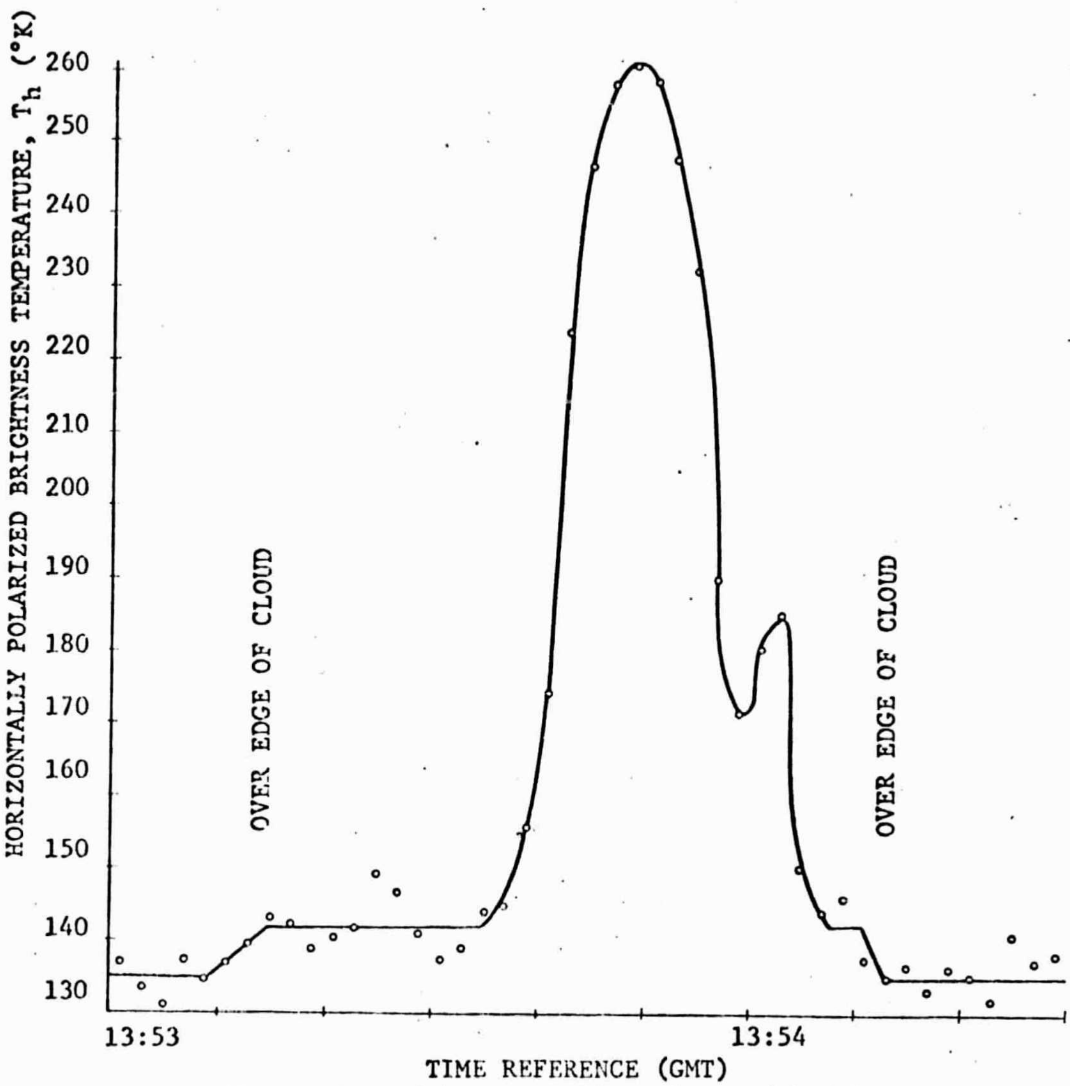
FIGURE 3-9



Measured values of the horizontally polarized brightness temperature from 17:24 Z to 17:25 Z during Flight 12 versus time for an incidence angle of 0° and for a frequency of 19.35 GHz as the aircraft flew from land to water.

(Paris 1969)

FIGURE 3-10



The estimated horizontally polarized brightness temperature from 13:53:00 Z to 13:54:30 Z during Flight 13 versus time for an incidence angle of 0° and for a frequency of 19.35 GHz as the aircraft flew over raining clouds at sea.

(Paris 1969)

FIGURE 3-11

was at approximately 0.6 km above the sea surface.

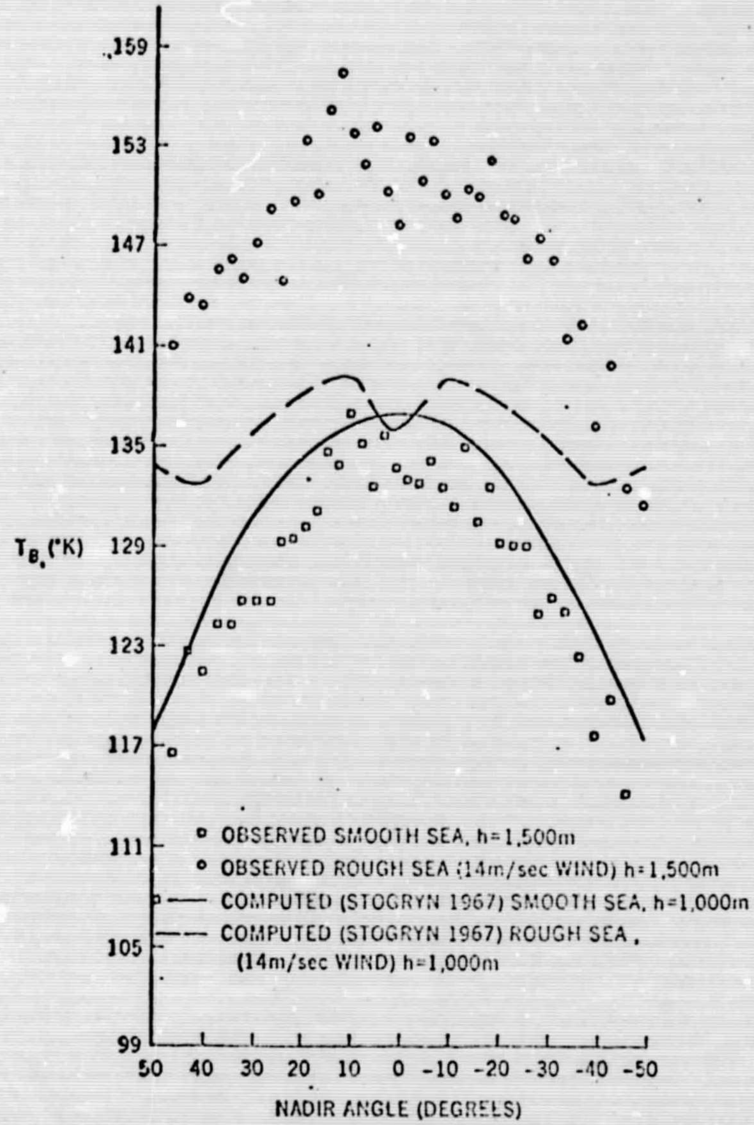
Nordberg et al (1969) have reported observations of sea state using the 19.35 GHz radiometer installed on the Convair 990. These measurements were performed over the Salton Sea in California. Observational data over the smooth sea appeared to be in close agreement with the Peake, Stogryn, and Sirounian models; however, a marked discrepancy was noted at all look angles of observation under rough sea conditions. A comparison of measured with predicted brightness temperatures as a function of look angle for the Salton Sea tests are shown in Figure 3-12.

The major discrepancy between model predictions and measurements is the apparent increase in the measured brightness temperature by approximately 20°K at all look angles under rough sea conditions. There was no rain at the time of the Salton Sea observations, though white-caps and foam, which are not considered in the analytical models, were visually observed.

A recent series of observational measurements were performed over the Irish Sea in March of 1969 by Nordberg et al, using the 19.35 GHz radiometer. The environmental conditions at the time of these measurements were far more extreme than conditions existing at the time of the Salton Sea tests. During the measurements over the Irish Sea, winds of up to 60 knots, with waves to heights of 40 feet, were observed during one day of observations near a weather front. Cumulus clouds and scattered rain showers typified atmospheric conditions. There were three significant factors derived from these measurements:

(1) The enhancement in brightness temperature at all look angles as typically observed in the Salton Sea tests was again observed in the Irish Sea tests.

(2) In an attempt to determine whether foam was a contributing factor, the Convair 990 was flown at 500 feet from the ocean surface. The observed brightness temperature, when the antenna beam projection was completely contained in a foam patch was measured to be nearly equivalent to the thermometric temperature of the ocean; i.e., the emissivity of the surface



Observed and computed (Stogryn 1967) brightness temperatures versus nadir angle at 1·55 cm over smooth and rough portions of the Salton Sea. Cumputations are for sea surface temperature of 290°K and a standard atmosphere. Observations were made with sea surface temperature of 294°K over the rough sea and 300°K over the smooth sea in a relatively moist atmosphere on 7 June 1968. Each point shown for the observed data represents an average of six consecutive scans at the respective nadir angle.

(Nordberg et al 1969)

FIGURE 3-12

approached unity. A careful measure of the percentage of foam patch cover, spatially distributed over the ocean's surface, however, indicated that the contribution to the observed brightness temperature, due to foam patches, would contribute at most approximately 2°K to the observed brightness temperature when the aircraft altitude was increased to provide a statistically integrated view of the ocean's surface. This was confirmed by measurement.

(3) When flying a ground track between a rain shower region and a clear region (no rain), an apparent temperature increase of approximately 20°K was observed in the direction of the shower. Lack of detailed knowledge concerning the characteristics of the rain did not allow determination of whether the observed increase in temperature was associated with rain on the surface or with the column of rain intercepted by the antenna beam.

One of the strongest proponents of the significance of interactions at the air-sea interface, particularly foam, formation of bubbles by rain, etc., has been G. F. Williams, Jr., of the University of Miami. Singer and Williams (1968) reported the detection of precipitation over the surface of the ocean using data obtained with the 15.8 GHz radiometer installed on the MSC Convair 240A. The detection was based on an observed increase in the observed brightness temperature over that predicted by the models of Stogryn and Sirounian. They concluded from their experiment that roughening of the ocean's surface by falling rain produces a small additional apparent temperature increase; however, winds above 15 knots provide a marked increase through the mechanism of foam generation. The pursuit of this hypothesis by Williams led to a second series of measurements which were performed in September 1967, when hurricane Beulah moved into the Gulf of Mexico. This offered the first attempt to perform a direct measurement of the effects of sea foam on apparent radiometric temperature under natural environmental conditions. The percentage of foam cover during these measurements was deduced from in-flight photographs of the sea surface.

Based on the results of these measurements and a series of measurements performed on the ground, using the NASA 926 aircraft, a predicted microwave temperature enhancement of the ocean versus wind speed has been developed by Williams. A graphical plot of this empirically determined relationship is shown in Figure 3-13. The observed values for hurricane Beulah are shown in this figure.

Several earth-based measurements and analytical models have been developed to describe the microwave emission properties of ice. The predicted and measured characteristics are in close agreement, showing that the emissivity of ice is approximately 0.9 when viewed in the nadir direction; hence, ice floating in water provides an excellent contrast, with the ice appearing much warmer than the surrounding sea water.

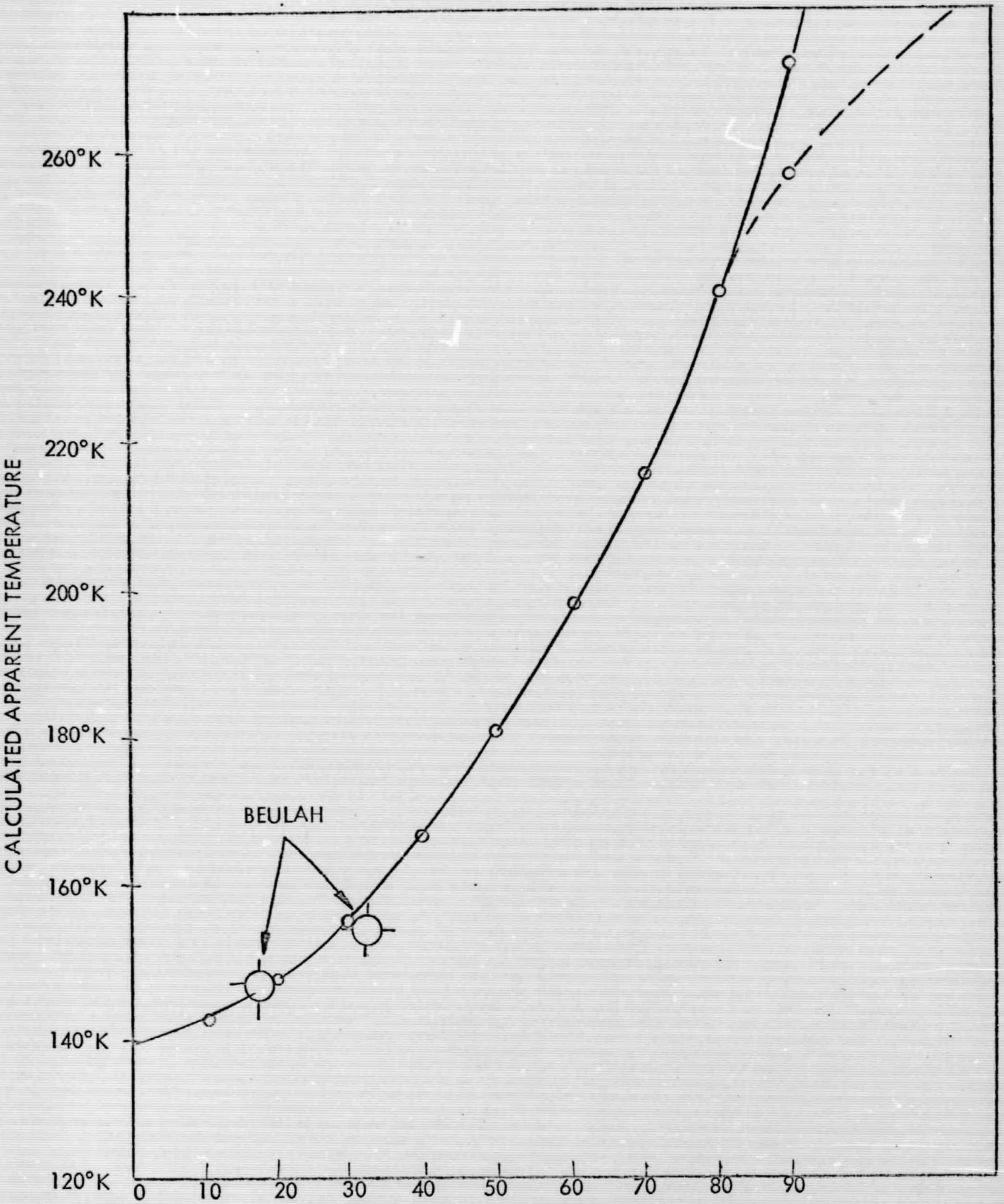
The large apparent temperature difference between ice and sea water has been applied to the detection of icebergs in the North Atlantic by the U. S. Coast Guard (Roeder 1967). The Coast Guard system operates in an imaging mode to maximize the water surface area coverage along the aircraft ground track.

<u>Summary</u>

The proposed applications of microwave radiometry in oceanography, based on the prognosis of Badgley and Vest (1966) are supported by relatively simple physical arguments derived from the physics of passive microwave remote sensing (see Appendix B).

The most advanced analytical models of Sirounian and Stogryn do not include consideration of such factors as rain, fog, hail, sea surface foam, or ocean salinity in their analysis of the potential of the microwave sensor to measure sea surface temperature and sea state.

Aircraft, as well as earth-based measurements, tend to confirm the significance of interactions which occur at the air-sea interface, such as bubbles formed by rain, foam, etc.



PROPOSED WIND vs. MICROWAVE TEMPERATURE CURVE

FIGURE 3-13 (Williams, 1968)

It would appear that the development of more complete analytical models, which include the various air-sea interface interactions, can be most fruitfully pursued through experimental measurements.

3.2 Geology and Hydrology

The ultimate users of geologic and hydrologic data include all peoples of the world, since these data are the basis of research exploration, leading to an understanding of the earth.

Water has long been a scarce resource in many parts of the world. It is now generally recognized that the development of water resources determines economic growth and places an upper limit on that growth.

The principal fields of applied geology are exploration for minerals, oil, and gas. Though airborne and spaceborne sensors sample to only limited depths, the passive microwave sensor at long wavelengths penetrates to the greatest depth, and hence provides a significant contribution to the sum total of information derived from all sensors.

Geology and hydrology include many remote sensing applications in common with geography, cartography, and agriculture. This, as a consequence of the fact that the physical reasoning in support of these potential passive microwave sensor applications, has many common denominators.

Potential Applications

The intimate interrelationship between geologic and hydrologic applications of passive microwave remote sensing is apparent from the listing provided by Badgley and Vest (1966), shown in Figures 3-2 and 3-3, respectively.

The geologic applications include:

- Rock types
- Porosity
- Permeability
- Fabric (growth)
- Coral reefs
- River effluence

Dunes

Stream, lake, bay deposit fans

Surface roughness

Soil moisture distribution

Permafrost

Heat balance, variations

Glaciation (continental, valley)

Several of the potential applications in the Badgley and Vest Report are shown with a question mark (?) indicative of some concern with analytical models.

The hydrologic applications listed in Figure 3-3 are:

Evapotranspiration

Rain distribution and infiltration

Ground water discharge

Water pollution

Run-off and water retention in glaciers

Water regimen of valley glaciers

Snow surveying

Erosion and sedimentation rates

The physical reasoning in support of these potential applications is predicated on the known and measured differences in emissivity for a large variety of terrain materials. Emphasis on hydrologic applications is associated primarily with the fact that the emissivity of water is markedly less than all other natural materials. The typical emissivities of natural solid materials are concentrated in the range from 0.9 to 1.0; whereas, the average emissivity of water is near 0.5.

Models

Analytical models of the microwave emission characteristics of a number of terrain materials have been the subject of several published papers. The works of Peake (1967) and Porter (1969) are quite representative. Models based on an sssumed semi-infinite homogeneous medium with relatively simple boundary surface characteristics are quite rigorous. The characteristics of the predicted radiation for several materials have been confirmed through direct measurement.

Extension of analytical model development from the simple semi-infinite homogenous model to multi-layered models and models which assume variation in layer distribution within the spatical resolution of observation, is a much needed next step. The complex models would be more typical of conditions in the real world for several areas of application. Those applications which involve a complex spatial distribution of materials that may be likened to a three-dimensional matrix, represent a significant challenge. Empiricism appears to be a logical approach to applications in this category.

The semi-infinite material applications, such as snow cover, degree of wetness of snow, and glacier characteristics, rank much higher in terms of near-future potential. Fortunately, applications in these areas have an equally high value rating. Glaciers, for example, cover approximately 11% of the earth's land surface; however, they are generally located in inaccessible regions where earth-based measurements are achieved at considerable expense and personal danger.

The processes of snow accumulation and wastage are dynamic; hence, the exploratory development of sensor applications require the accumulation of observational data in sufficient frequency to define the nature of these events.

A significant characteristic of the various model developments in this major area of application is emphasis on the wavelength of observation as the most important parameter - this as a consequence of the wavelength dependent penetration depth afforded by microwave sensing.

Measurements

During the past two decades, most of the major Government and industrial research laboratories have reported the results of either earth-based or aircraft measurements for a variety of terrain materials. An excellent summary of these research efforts can be found in the recent works of Paris (1969) and Porter (1969). Three recent measurement programs have been selected for discussion here as representative of current trends in earth-based and aircraft measurements. The earth-based measurements reported by Edgerton (1968) are considered representative of present geologic measurements. The earth-based measurement of snow wetness factors, reported by Kennedy and Sakamoto,(1966) are typical of hydrologic applications. Blinn et al (1968) published a very detailed description of an experimental program combining the results of airborne and earth-based measurements in the multi-frequency microwave sensing of an exposed volcanic province. The published account of this research effort (JPL Technical Memorandum 33-405) provides considerable insight concerning the various phases of the planning and execution of an airborne measurement program.

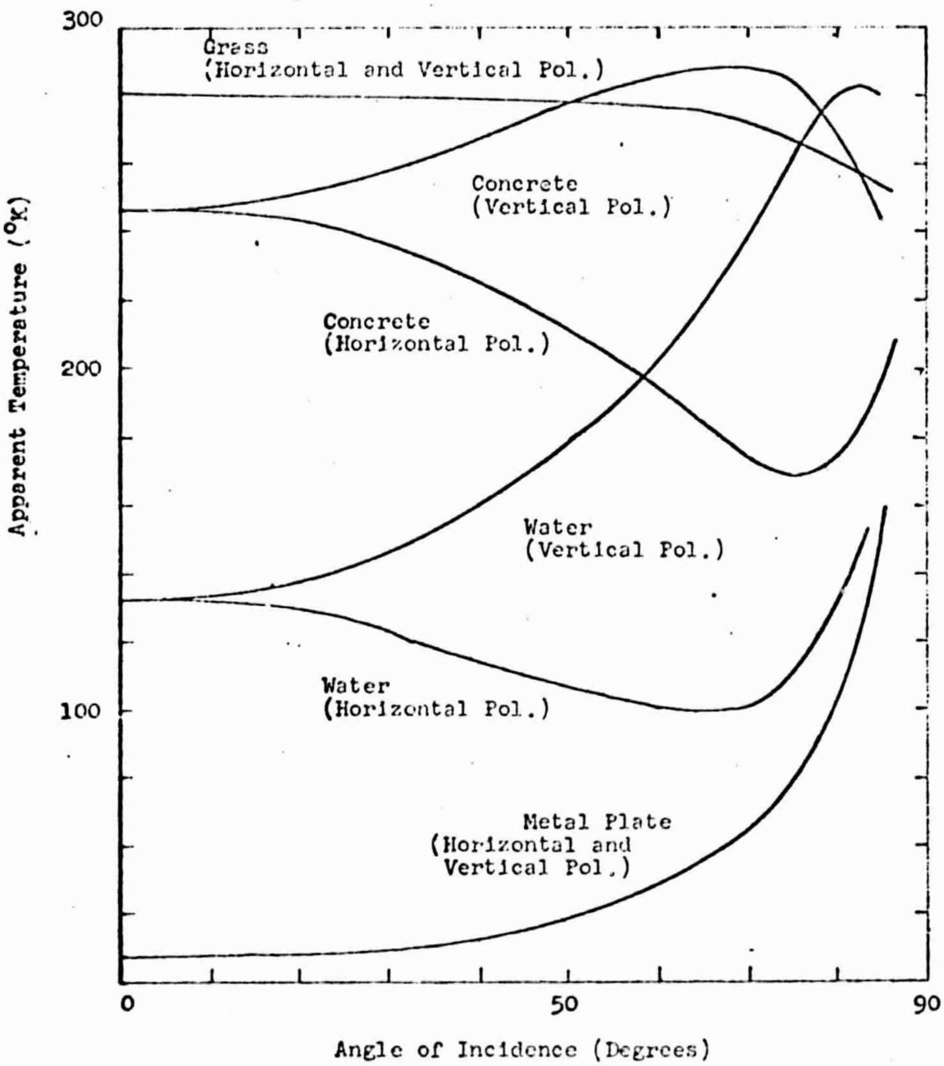
Edgerton (1968) has described recent research concerning the utilization of microwave radiometers for terrain analysis. This work was performed under the sponsorship of the Office of Naval Research, the Air Force Cambridge Research Laboratory, and the Army Cold Regions Research and Engineering Laboratory. The objective of these earth-based measurements was to establish the microwave characteristics of a number of soil materials.

The radiometer system used for these field studies consisted of a three-frequency dual polarization radiometric sensor housed in a 16-foot mobile van type trailer laboratory. The truck portion served as a mounting platform for the diesel power generator and the radiometer sensor head mounting boom. Remote control of the boom provided positioning of the radiometric sensor look angle in both azimuth and elevation. The data display for an instrument of this type is frequently referred to as a "parametric display" in which the observed brightness temperature is displayed as a function of the elevation look angle in two orthogonal polarizations.

To provide a comparative analysis of the measured data with that predicted by analytical models, several materials were selected and the anticipated parametric relationships computed. The computational methods were similar to those described by Porter (1969). In the analytical development of the examples shown in Figure 3-14, the thermometric temperature of the surfaces was assumed to be 290°K, the observing frequency was 19.4 GHz, and the reflected component of radiation was based on a standard atmosphere. Referring to this figure, it is of interest to note that grass behaves as a rough surface and shows no polarization dependence. The observed apparent temperature is almost equal to the thermometric temperature and exhibits a negligible look angle dependence. In contrast, a metallic plate which exhibits near zero emissivity emphasizes the reflected component which is predominantly sky noise. The increase in the observed apparent temperature with look angle follows the "secant law" as anticipated.

The apparent temperatures of a smooth water surface and of concrete with emissivities intermediate between grass (1.0) and a metallic plate (0) show the effect of the dielectric constant on the apparent temperature of smooth surfaces. Both water and concrete also show polarization effects which are typical of most dielectric materials. The maximum which occurs in the vertically polarized temperature is nearly equal to the thermometric temperature of the surface. The look angle at which the maximum occurs is dependent on the dielectric constant of the material. The larger the dielectric constant, the larger the look angle at which the maximum occurs.

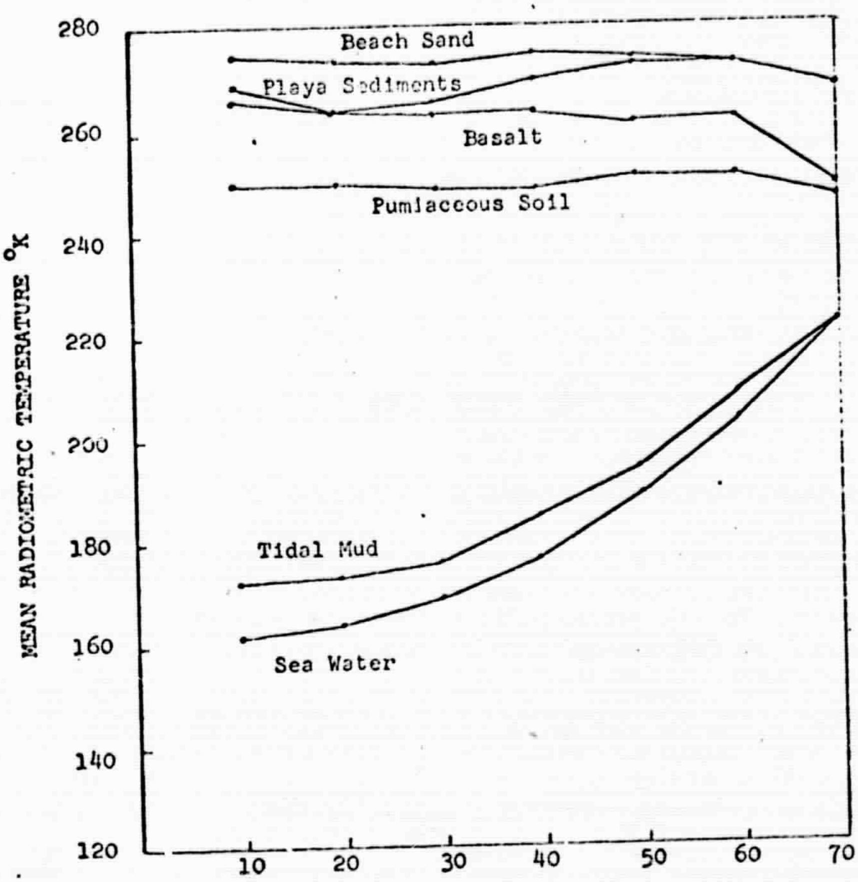
A composite parametric display of the vertical polarization temperatures of six materials, measured at 37 GHz (Edgerton 1968), is shown in Figure 3-15. It is of interest to note the general close agreement between predicted and measured data. The two lower curves shown in Figure 3-15, mud and sea water, are data obtained from a tidal marsh near San Francisco, California. The playa sediments and pumiceous soil exhibit characteristics similar to those one might anticipate for dry natural materials. The water content of the



APPARENT TEMPERATURES OF SURFACES AT 19.4 GHZ

(Edgerton 1968)

FIGURE 3-14



COMPARISON OF RADIOMETRIC TEMPERATURES, 37 GHZ VERTICAL POLARIZATION

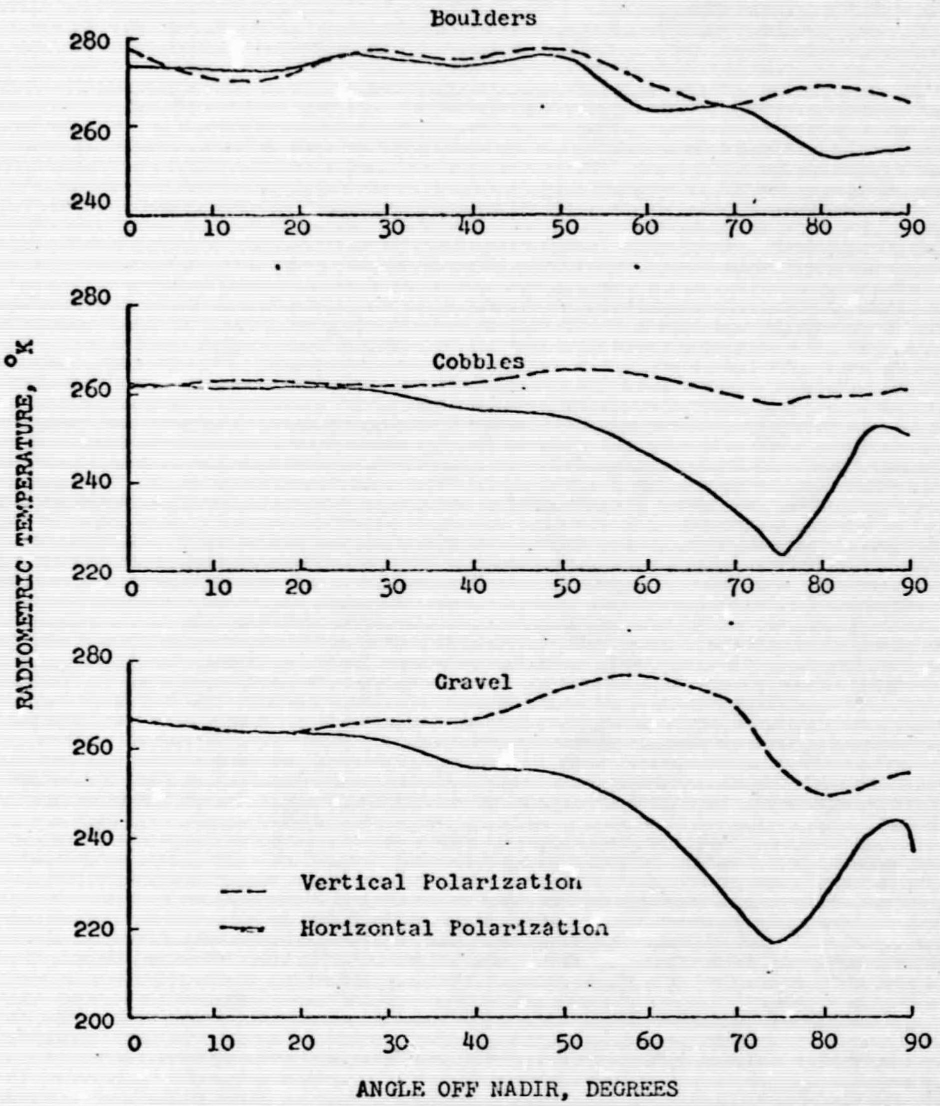
(Edgerton 1968)

FIGURE 3-15

sand-water mixture (mud) increases the reflectivity of the composite material and decreases the emissivity. In general, the curve shape for dry soils is dominated by the emissivity function, while the curve behavior of wet soils is determined primarily by the reflectivity.

The gross effects of surface roughness are illustrated in Figure 3-16 (Edgerton 1968). The parametric curves shown at the top in this figure were obtained when observing boulders several feet in diameter. The temperature variations, as a function of look angle in this case, are due to local topography which affects the angle of observation; i.e., incidence angle. The material used for development of the center curve, labelled "cobbles" was obtained by passing samples through a 10 cm X 15 cm mesh screen. It is of interest to note that the material of this size shows some of the characteristics of a rough surface and some of a specular surface. The vertically polarized component tends to indicate a maximum which is even more conspicuous for gravel shown in the lower graph.

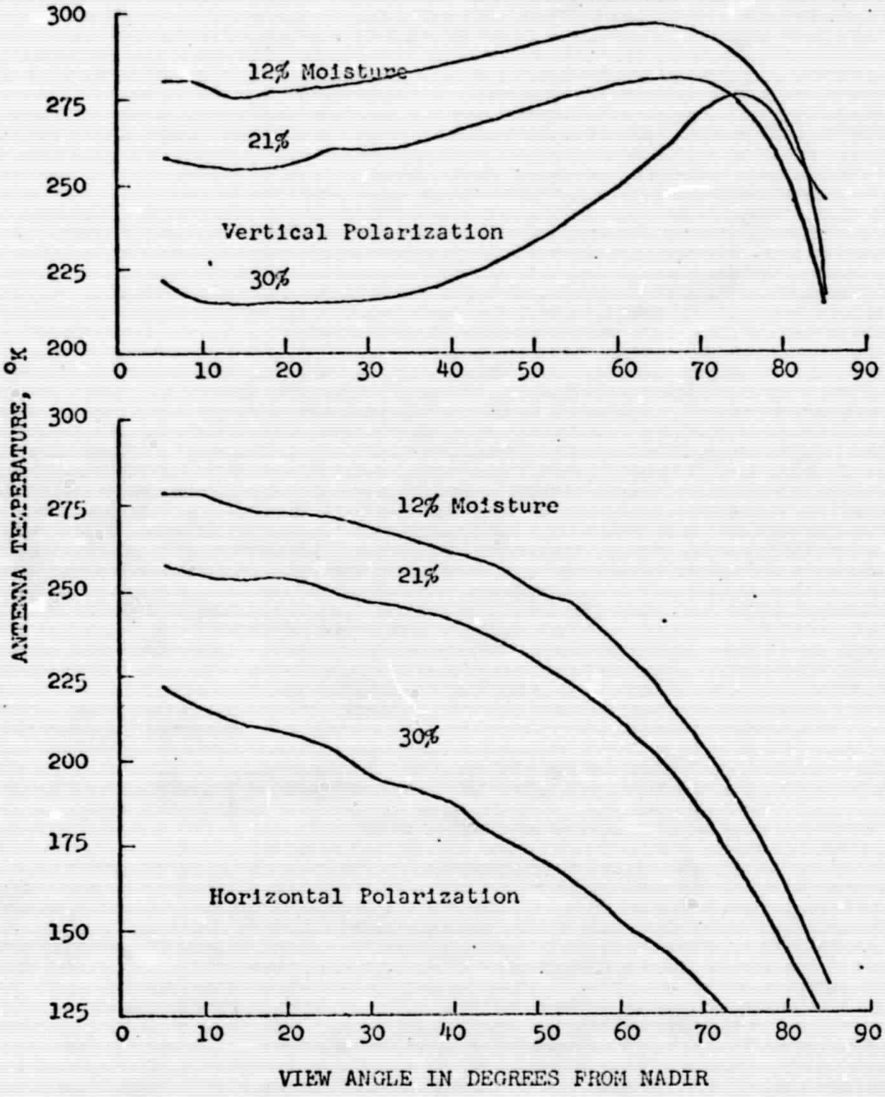
The measurements reported by Edgerton (1968) included a playa deposit in the Mohave Desert, California, to investigate the relationship between radiometric temperature and soil moisture content. The material composition, in grade and size, of the playa observed in these measurements was very uniform. Consequently, the only significant variable in these measurements was the near-subsurface water content and some minor differences in surface temperatures. The results of these measurements are shown in Figure 3-17. The moisture content of the soil is shown in this figure as percentage water by weight for the upper six-inches of the material. It can be seen from these measurements that the microwave temperature for both horizontal and vertical polarization is a strong function of water content. The greater the water content of the soil, the lower the observed radiometric temperature. As the moisture content increases, the difference between horizontal and vertical polarization temperatures increases, showing that reflectivity is a significant factor. Further, as one might anticipate, the more moist the soil, the higher the dielectric constant; and consequently, the larger the look angle at which the maximum occurs in the vertical polarization temperature.



- RADIOMETRIC TEMPERATURE PROFILES OF BOULDERS COBBLES AND GRAVEL AT 13.5 GHZ

(Edgerton 1968)

FIGURE 3-16



13.4 GHZ RADIOMETRIC TEMPERATURES OF PLAYA SEDIMENTS WITH VARIABLE MOISTURE

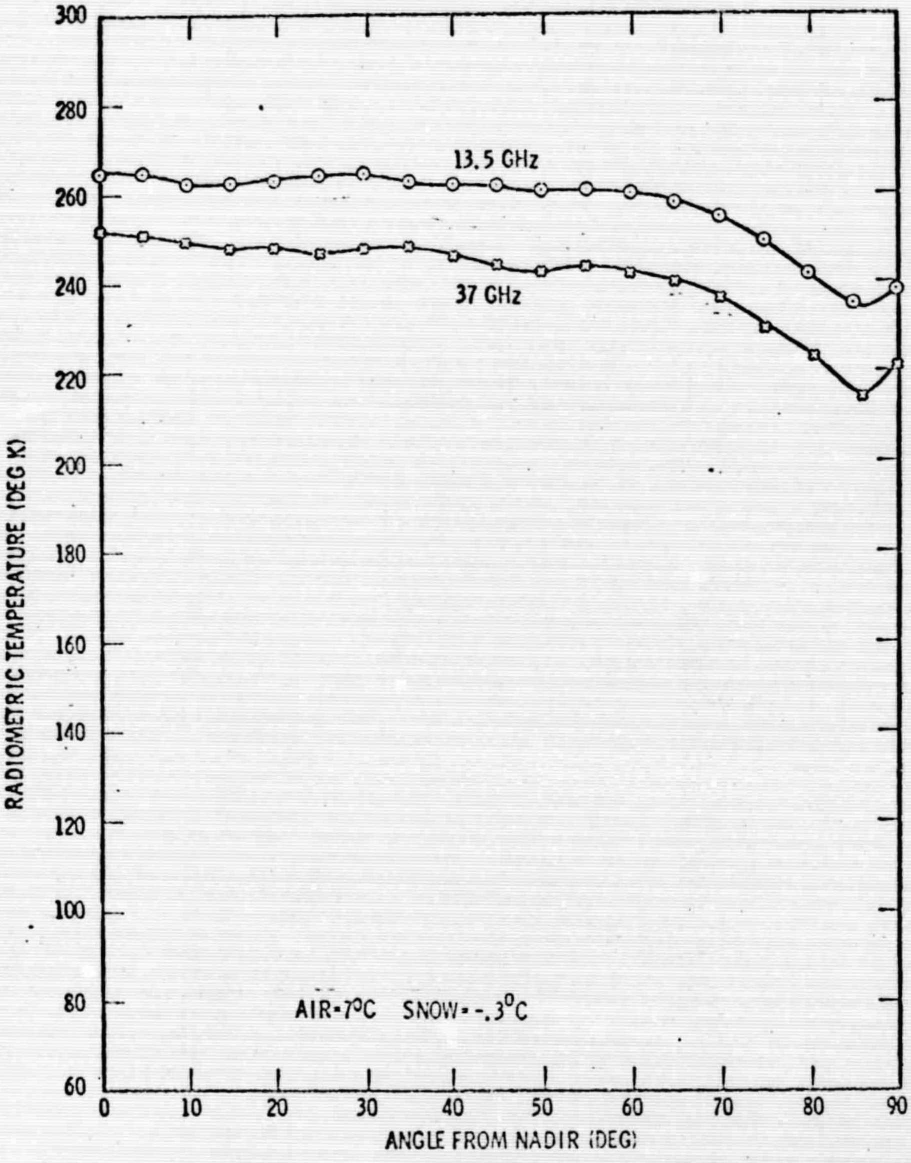
(Edgerton 1968)

FIGURE 3-17

It is of interest to note that the measurements reported by Edgerton were devoted primarily to soil characteristics. However, the moisture content of soil was particularly significant and has an important bearing on several hydrologic applications such as the mapping of the subsurface water table. Though a comparison of data obtained at various wavelengths was not included in the Edgerton report, it is readily apparent from the consistency between model predictions and measurements that the longer wavelengths would show evidence of greater depth of penetration below the surface.

Earth-based measurements of snow wetness factors have been reported by Kennedy and Sakamoto (1967). These field measurements were performed at Crater Lake National Park in Oregon. The radiometric instrumentation used for these measurements was the same as that used in the measurements reported by Edgerton (1968). The horizontally and vertically polarized brightness temperatures of snow measured at 13.5 GHz and 37 GHz reported by Kennedy and Sakamoto, are shown in Figures 3-18 and 3-19, respectively. These measurements show that the parametric display is relatively flat in either polarization between the nadir position and 30° off nadir, an important consideration in the development of an airborne or spaceborne imaging display.

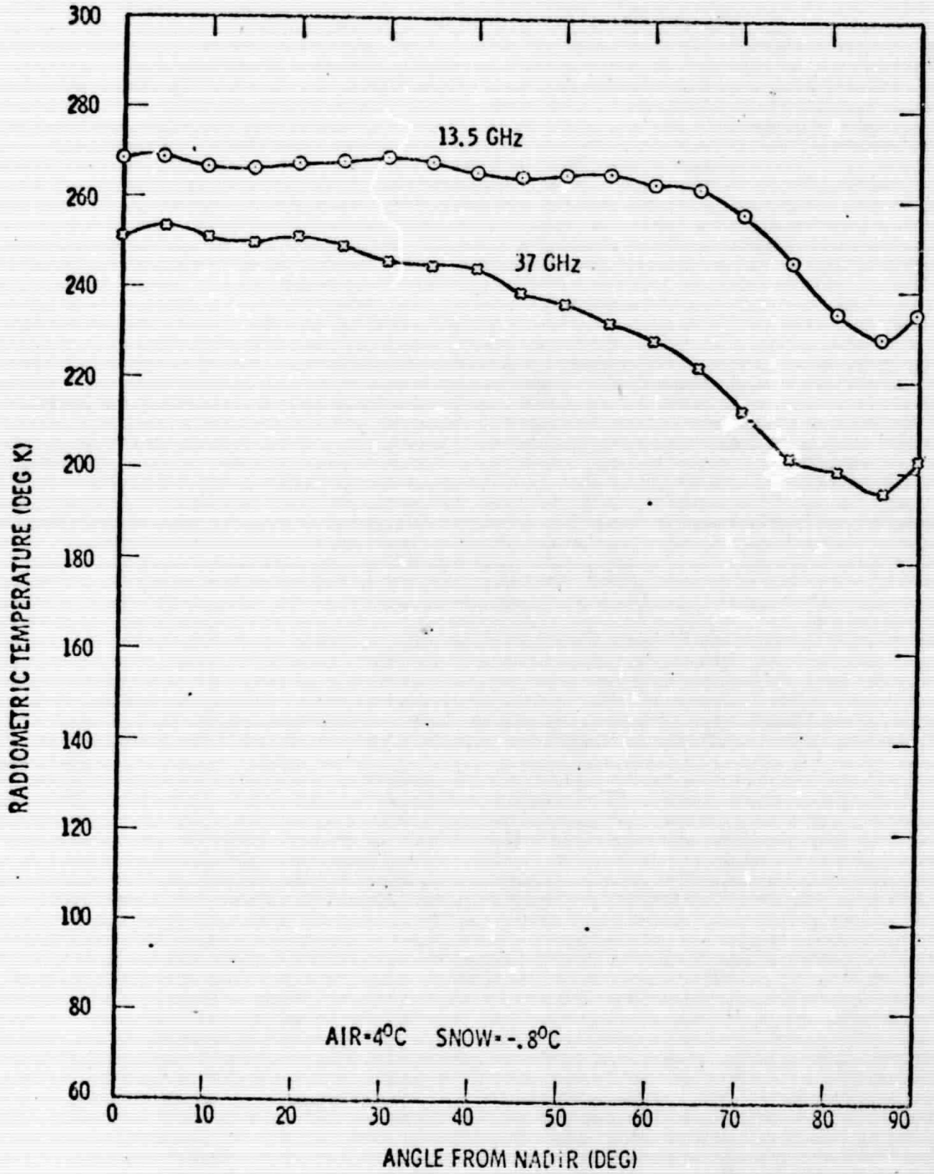
A series of measurements were performed under semi-controlled conditions by introducing an aluminum plate underlying the snow (the plate was placed in position prior to snowfall). The aluminum plate furnished a known-background condition eliminating the uncertainity that would be present with a snow-soil interface. Though the introduction of the plate appeared to be a simple solution, the observational data was strongly affected by the accumulation of a slush layer approximately 3/4" thick with a free water content in excess of 40% directly over the plate, in addition to the thick film of pure water adjacent to the plate. To overcome these difficulties, the measurements were repeated under similar environmental conditions with pumiceous soil replacing the aluminum plate. Though the results were similar, the complex-soil background reduced the brightness temperature



Vertical Brightness Temperature of Snow.

(Kennedy, Sakamoto 1966)

FIGURE 3-18



Horizontal Brightness Temperature of Snow.

(Kennedy, Sakamoto 1966)

FIGURE 3-19

contrast. These measurements emphasized the difficulty that one experiences in attempting to isolate a material sample in its natural environment.

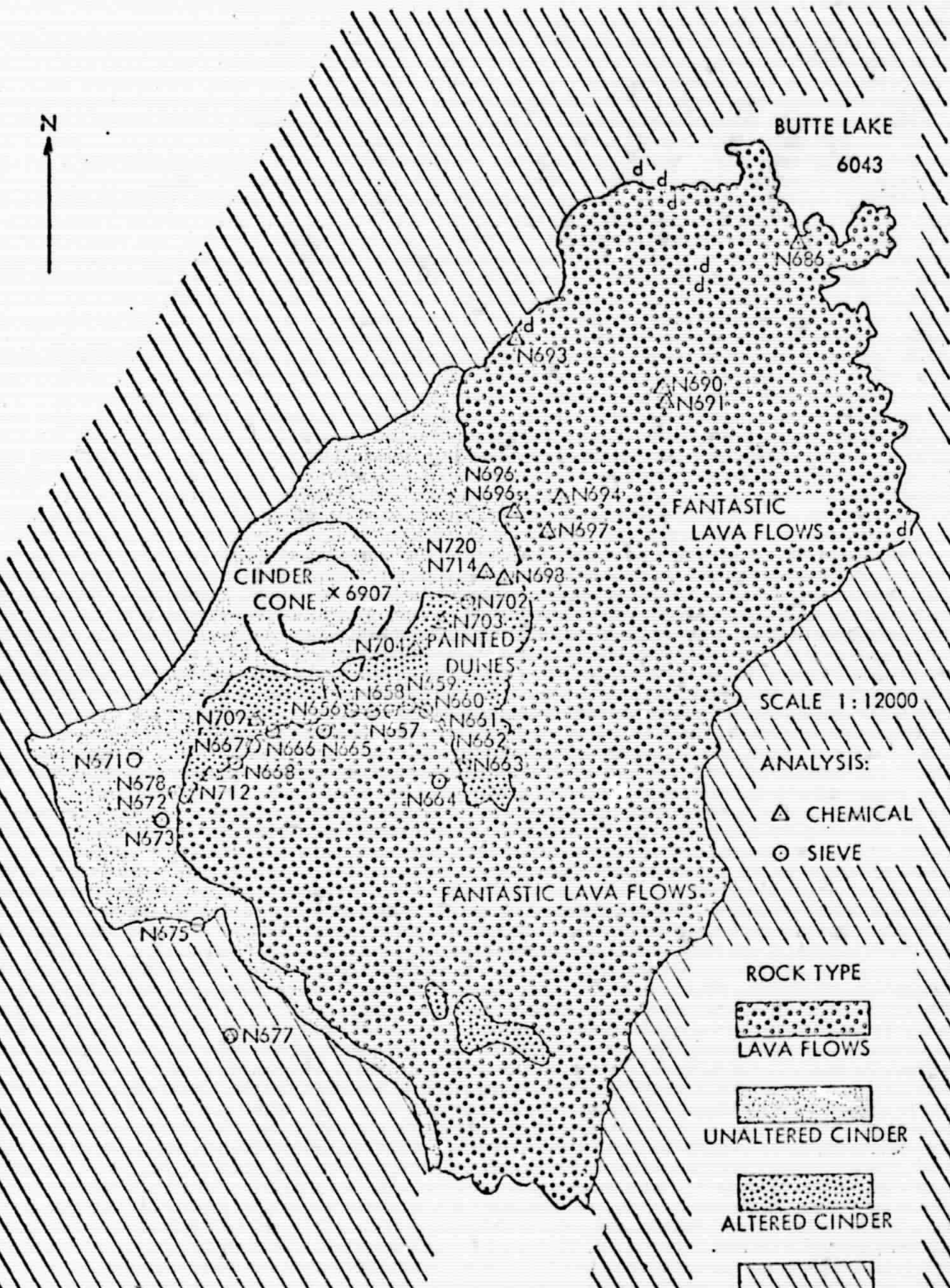
It was concluded by Kennedy and Sakamoto that an empirical relationship could be established between the radiometric brightness temperature and the percentage of free water contained in snow.

From the standpoint of significance to geologic applications, the aircraft measurements reported by Blinn (1968) are representative of current capabilities as well as the level of effort required. The objective of this airborne measurement program was to determine correlations between multi-spectral microwave radiometric signatures and geologic parameters. Multi-frequency microwave radiometric measurements were performed on an exposed volcanic province in the vicinity of Mount Lassen, California. The NASA remote sensing Convair 240A aircraft, NASA-926, was used for these measurements. The MR-62 and MR-64 radiometric sensors installed on this aircraft are described elsewhere in this report (see Section 3.1).

The Mount Lassen test site was selected because it is relatively flat and contains large homogenous areas of material with similar chemical composition.

The investigation of ground parameters at the Mount Lassen site was initiated two months prior to the airborne measurements. The ground parameter measurements included standard geologic mapping, particle size determination, petrographic and chemical studies, as well as density and moisture measurements. The chemical and petrographic measurements were established along the general area of the flight lines. The location of the ground measurement samples and the general layout of the test site in the vicinity of Mount Lassen is shown in Figure 3-20.

Two flight lines were chosen to utilize the characteristics of the terrain to the fullest extent. Both originated over lakes which offered a geographic reference for the flight lines and calibration points for the radiometer data. The ground tracks for the two



Sample location map showing sampling points for preflight studies

(Blinn et. al. 1968)

FIGURE 3-20

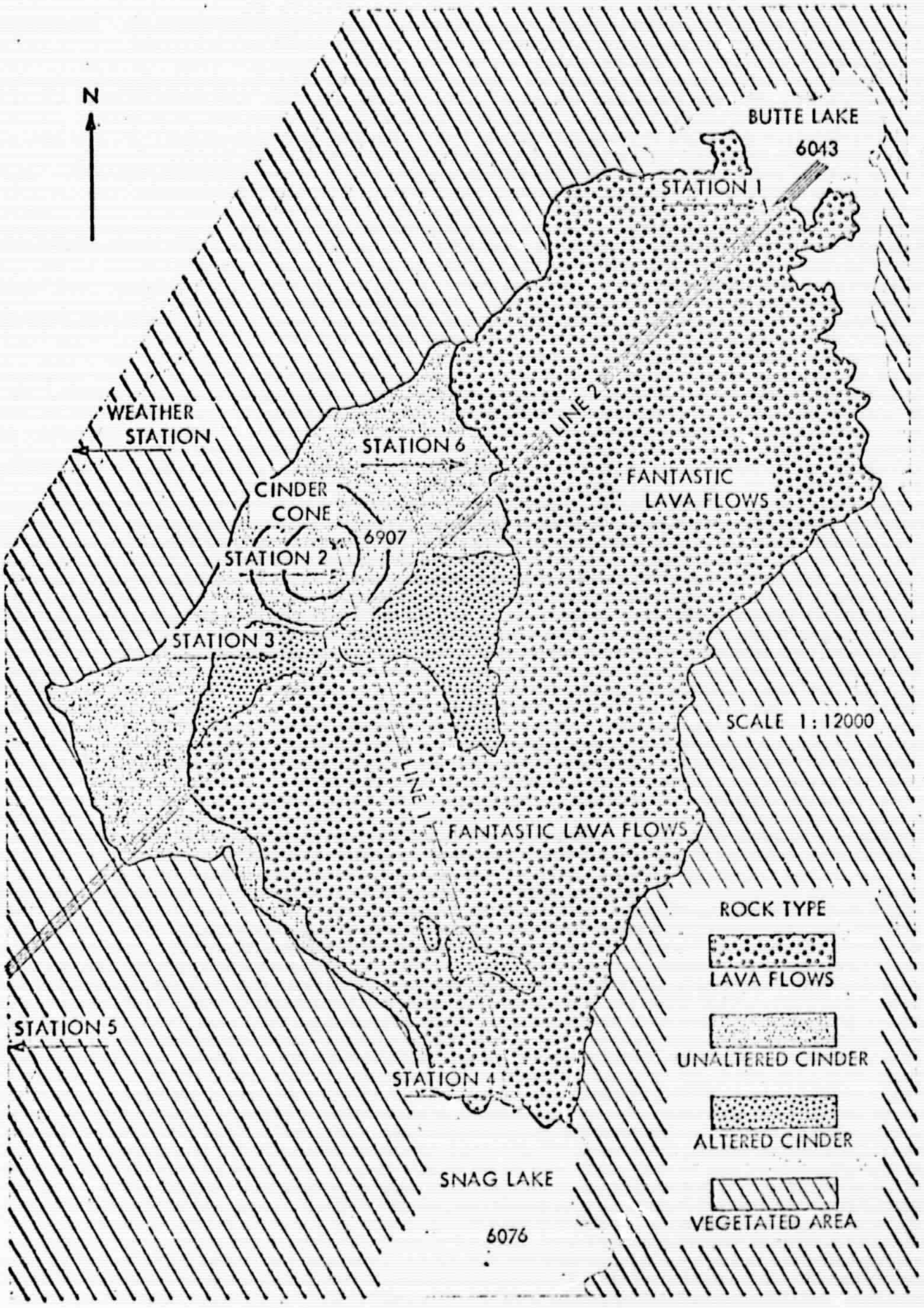
flight lines are shown in Figure 3-21. Line 1 was flown south to north, and line 2 from northeast to southwest in a figure 8 pattern. Four runs were flown over each line in the same direction and at constant altitude. Two flights were required to obtain data in both vertical and horizontal polarization at two look angles of 10° and 45°.

In order to maximize spatial resolution, the aircraft was flown at the lowest possible flight altitude. Low level turbulence during the day and aircraft safety at night established the flight altitude at approximately 4,000 feet, day or night.

Average measured values of antenna temperature over water, lava, and unaltered cinder measured at night are shown in Figure 3-22A. The average of daytime observations over the same area are shown in Figure 3-22B.

As noted by Blinn, there are several factors that may contribute to the observed apparent temperature difference between lava and unaltered cinder such as chemical composition, moisture content, surface characteristics, microwave penetration depth and thermal properties. Since the chemical composition of the cinder and lava were essentially the same, this was eliminated as a contributing factor. Moisture would have the effect of lowering the brightness temperature and decreasing the depth of penetration as previously described. However, the moisture content was low for both materials and the microwave return did not show consistently cooler temperatures at all frequencies over either of the materials. Surface roughness would tend to affect the cooling rate, and hence the microwave brightness temperature; however, one would anticipate that these effects would cause consistent trends in the data. This was not supported by the observations and hence moisture content and surface roughness were eliminated as controlling factors.

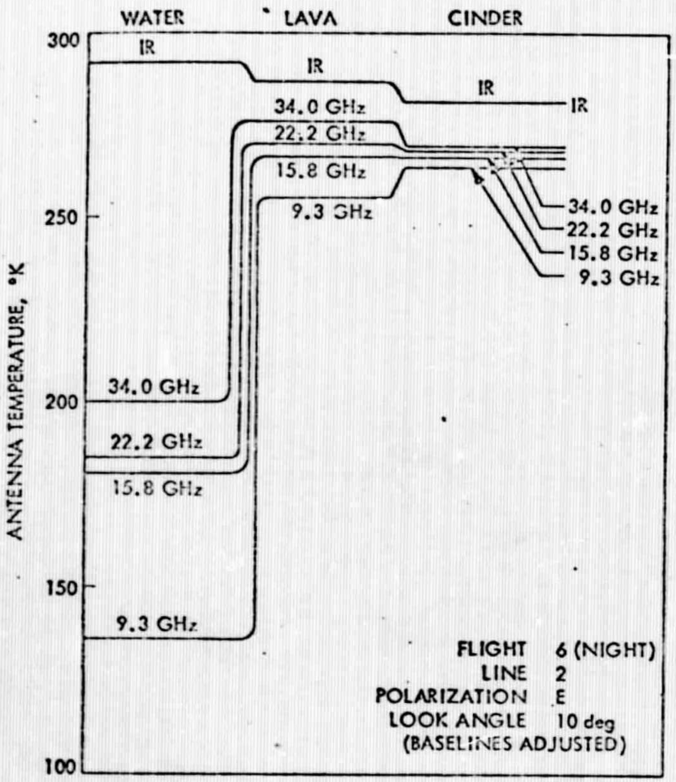
Based on the foregoing arguments, the radiometric penetration depth was considered to be significant by Blinn. If the penetration depth of the cinder were greater than that of the basalt and all other factors were equal, the 9.3 GHz observations would show the cinder to be warmer than the lava at night, as indicated by the data. One would anticipate, however, that the surface temperature would be the same for both



Locations of overflight stations

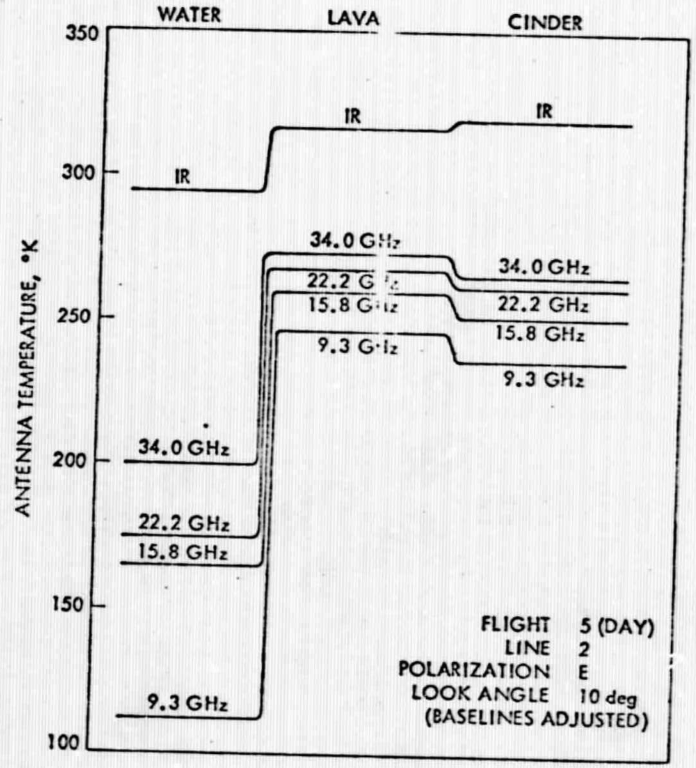
(Blinn, et al, 1968)

FIGURE 3-21



Radiometer responses over water, lava, and cinder, flight 6, diagrammatic representation

FIGURE 3-22A



Radiometer responses over water, lava, and cinder, flight 5, diagrammatic representation

FIGURE 3-22B

FIGURE 3-22

(Blinn, et al, 1968)

materials. This was not supported by the IR and 34 GHz data. This led Blinn to the conclusion that the most important factor in the observed response was heat conduction, i.e., thermal properties of the material. The better of two thermal conducting materials will show a warmer surface temperature and a cooler temperature with depth during the night. (The interrelationship between the heat wave which is determined by the thermal properties of a material and the electromagnetic wave emitted by a material is described in greater detail in Section 4.1).

Blinn (1968) concluded that the wavelength dependent penetration depth capability of the multi-frequency radiometer provides a significant contribution to the observed apparent temperatures; however, the cinder, because of its porosity is not as good a thermal conductor as basalt, and hence the differences in the thermal properties of the materials were the controlling factor.

Based on the conclusions and recommendations, suggested by Blinn as a result of his measurements the following comments can be made, paraphrased in the context of related conclusions and recommendations derived as a result of this study:

(1) Determination of the effect of individual geologic parameters on the observed apparent microwave temperatures can be most easily accomplished if a relatively simple test site is selected; i.e., one which is susceptible to analysis of features using semi-infinite homogenous models.

(2) Ground truth data is critical to the interpretation of observational data.

(3) Sensor systems which require mechanical adjustment

of look angle and polarization complicate both the flight requirements, as well as the data reduction procedures.

(4) Provision for in-flight calibration of equipment is highly desirable.

In addition to the above list of conclusions concerning the planning and implementation phases of any experiment, Blinn was able, as a result of this measurement program, to arrive at the following conclusions concerning the potential of microwave radiometry to geological applications:

(1) There is a definite correlation between basic geologic units and radiometrically observed temperatures.

(2) Long wavelength observations are capable of sensing subsurface temperatures.

(3) There is an apparent correlation between subsurface layer thickness and the multi-spectral return for a layered area.

(4) A difference in the surface roughness of two chemically similar areas is detectable with a dual polarization radiometer.

<u>Summary</u>

Geologic and hydrologic applications of passive microwave radiometry, as outlined by Badgley and Vest (1966), are supported by physical reasoning derived from the interaction of those parameters of natural materials which determine the observed microwave temperature.

Most analytical model studies and supporting measurements, to date, have been devoted to the case of semi-infinite homogenous material, i.e., one material composition observed under various environmental conditions.

Parametric displays have dominated both the analytical model studies and measurement efforts in this major area of application - indicative of the need for a data form more susceptible to physical interpretation than provided by an image display.

Hydrologic applications, such as soil moisture content, subsurface water table detection, snow water content, and glacial characteristics appear to offer greater near-future potential as a consequence of the large signal contrast induced by the presence of water.

The extensive measurement data available confirms the general hypotheses concerning those material and environmental parameters which determine observed microwave temperatures. An empirical approach, utilizing improvements in the sensitivity and calibration of radiometers is suggested as the most fruitful avenue in support of further research in this area.

Field measurements require considerable care in both planning and execution. Separation of an observed sample from its natural environment is a critical concern.

Depth of penetration which is nearly proportional to the wavelength of observation appears to be the most significant parameter for geologic, as well as hydrologic applications. The long wavelength region, however, has been excluded from earth-based measurements as a consequence of the far field requirement associated with a useful antenna beam angle resolution. In addition, the exploitation of this very important parameter (low frequencies) is not suited to most piston and jet-type aircraft, as a consequence of the relatively large antenna aperture diameter equired. Helicopters and blimps appear to be more suitable observing platforms for experimental activities.

3.3 Geography and Cartography

Geographical studies deal with both the physical and cultural distribution pattern characteristics of the earth. The interpretation of these patterns establishes the intimate interrelationship between geography and other disciplines such as cartography, forestry, and agriculture.

Cartography is the depiction of the physical surface of the earth on maps useful to scientific and engineering disciplines. Accurate topographic maps are a necessary tool for geologic and mineral resource surveys, marine geology and hydrology studies, water resources inventory, land utilization studies, etc.

Knowledge concerning global land-use patterns is one of the most significant indicators of man's strategy for coping with his environment; hence, the intimate relationship between geography and cartography. The dynamic nature of these land-use patterns are the results of complex socio-economic decisions and interactions. Knowledge of these patterns would undoubtedly aid in attempting to understand the complexity of the motivating decisions and interactions. It would certainly aid in predicting future land-use patterns.

Applications

Specific applications presented in the prognosis of Badgley and Vest (1966) represent a logical derivation from the forgoing discussion. The geographic applications, for example, taken directly from Figure 3-4 include:

- Land use
- Urban studies
- Vegetation cover and soils
- Glaciology and Permafrost

Cartographic applications were included in the prognosis of Badgley and Vest under

"Geologic and Geographic Applications." It is the cartographic feature of these geographic applications that leads to the selection of the microwave imager as the sensor mode most useful in this major area of application.

Models and Measurements

Geographic and cartographic applications place considerable emphasis on the mapping of cultural, as well as natural, resources. Consequently, the analytical models and associated supporting measurements must consider the microwave signature characteristics of man-made as well natural materials. The radiation characteristics of natural materials are discussed in the prior section devoted to geology and hydrology. Also in that section, an experiment was described in which an aluminum plate was used as a base line reference. The near zero emissivity of this metallic conductor leads to an observed microwave temperature determined almost solely by the reflected component which has as its source, sky noise. Thus the plate appears cold and hence would appear as an anomaly in a characteristically warm natural environment.

The majority of analytical as well as supporting measurements devoted to the prediction of the radio signature characteristics of man-made materials have been sponsored by the Department of Defense. The results of the associated earth-based as well as airborne measurements support the ability to detect and map man-made materials interspersed in a natural environment. Cities represent a relatively simple example. From the prior discussion of emissivity differences between asphalt, grass, and water (see Figure 3-14), one can easily visualize a microwave map of New York City. The population of concrete in lower Manhattan, and the vegetation of Central Park outlined by the East, Hudson, and Harlem Rivers would show a "warm" Central Park surrounded by "microwave cool" rivers, with an intermediate temperature slightly less than Central Park assigned to the concrete buildings and streets. During or shortly after a rainfall, the streets would standout in sharp contrast, appearing cool like the rivers. Applying similar natural emissivity contrast logic, one can easily visualize a radiometric picture of Boston and the Cape Cod hook forming the Bay.

Summary

The extension of microwave radiometric sensing to the mapping of cultural resources is supported both analytically as well as by measurement. The achievable angular resolution, however, is approximately two orders of magnitude less than that available in optical photography. Consequently, the role of the passive microwave radiometer in geographic and cartographic applications is in those supporting contributions where observations under overcast weather conditions, or where depth of penetration below the surface is an important factor. Here again the significance of the low frequency region emerges as an important consideration.

3.4 Agriculture and Forestry

Agriculture is an international business. It involves the producing, processing, financing, supplying, and distributing of food and fibre. It is the major component of any domestic economy. The development of a sound economic base requires an accurate inventory and a timely continuing accessment of food and fibre resources on a global basis. At present, this type of information is generally available for the United States. In several developing countries, this information is non-existent or inadequate.

Forest lands are used for production of many goods and services, in addition to wood. Wildlife which provides food as well as recreation depends to a great extent upon maintenance of suitable forests or other wildland habitat. Forest lands are also a major source of water for agriculture, industry, and municipalities. Though wood and wood products have been a mainstay in the economic development of our nation and of most other nations of the world, many of the tropical countries are barely in the exploitation stage of forest-land use. These countries would benefit from an appropriate inventory analysis of their forest resources as an aid in the logical progression to careful utilization and sustained production.

Applications

Passive microwave applications in agriculture and forestry based on the prognosis of Badgley and Vest (1966), taken directly from Figure 3-5, include:

Topography

Irrigation water (snowpack)

Soil moisture

Fire detection (prediction)

Soil temperature

Damage assessment (flood)

In the course of this study, we were fortunate to review USDA requirements in personal discussions with members of the Department. We learned as a result of these discussions that the USDA is particularly desirous of an all-weather surveillance capability. This need is based on USDA responsibility to the Office of Emergency Planning in natural disaster situations which involve communities with populations of less than 10,000 people. The USDA performs an inter-agency service organization function in the accumulation of observational data required for emergency planning decisions. In such instances, the determination of whether a community is, or is not, qualified to receive federal relief funds often necessitates the use of documented evidence of damage that is of a photographic nature (map). In discharging this responsibility, the USDA feels that on occasion, overcast weather conditions at the time of a disaster seriously hamper the opportunity to obtain maps on a timely basis.

Analytical Models and Measurements

The physical reasoning in support of the anticipated agriculture and forestry applications can be derived directly from the discussion presented in Sections 3.2 and 3.3. The application to topography, for example, is based on the ability to sense surface roughness. The "water content" related applications, such as: irrigation water (snowpack), soil moisture and damage assessment (floods) are all based on the relatively low value of water emissivity (0.5) in comparison with the emissivity of other natural materials.

The ability to remotely sense soil temperature is predicated on the dependence of the radiated flux on the thermometric temperature of the soil. From the foregoing discussion, however, it is apparent that the emissivity of the soil must be known as well as the moisture content.

Though the emissivity, thermometric temperature, and variations in moisture content (which affect emissivity) determine the outgoing microwave radiation from the material's surface, it is important to recognize that in agricultural applications, the material under surveillance is known. The prime objective of remote sensing is to establish the condition of material and not to identify it. The subtle distinction between the problem of identifying an unknown material and the relatively more simple problem of establishing the condition of a known material is worthy of note. The complexity associated with identifying an unknown material from its microwave signature has, on occasion, represented a stumbling block in the "thought" process of microwave physicists approaching the field of Earth Resource applications. When it is recognized that the problem is to establish the condition of a known material, the physicists tend to rate this possibility with a far greater degree of confidence.

Measurements in support of the agricultural applications listed above are covered elsewhere in this report as they bear an intimate relationship to applications in the field of geology and hydrology. Perhaps, the only notable exception is the detection of forest fires. The ability of a microwave radiometer to detect the central core of a forest fire in the Los Angeles area was demonstrated at least once by the Aerojet General Corporation. The infrequency of observations of this type is related primarily to the availability of an airborne microwave radiometer at the time of a forest fire, rather than any question concerning the efficacy of this application.

<u>Summary</u>

The majority of anticipated applications of passive microwave radiometry in agriculture and forestry are common to applications in geology and hydrology. The major areas of near future benefit appear to be soil moisture content and the detection of the water table as an aid in predicting irrigation requirements. Here again, the use of multi-spectral imaging, using a large range of observing wavelengths, will afford the opportunity to determine the water table level as a function of time. The longer the wavelength, the deeper the penetration below the surface.

Applications involving crop damage assessment as a result of disease, etc., fall in the category of complex models which require a more detailed understanding of the associated biological processes and the relationship of these processes to the observable microwave radiation characteristics. Progress in these areas would benefit through further laboratory measurements and supporting analytical studies followed by measurements obtained under controlled conditions from aircraft platforms.

4.0 ADVANCED TECHNOLOGY REQUIREMENTS

From a technical standpoint, it was of considerable surprise to us to learn that little, if any, experimental effort has been devoted to the low frequency region (0.3 to 2.0 GHz) since physical reasoning in support of the potential benefits certainly appear to outweigh the attendant difficulties. Compromise and accommodation appear to have played a dominant role thus far, with predictable results. Present-day sensors are designed to accommodate the restraints imposed by high speed airborne platforms. High-frequency systems are more easily mated to these airframes. Appropriate low frequency measurements cannot be performed on the ground. Exploitation of the low frequency region has been excluded for these simple reasons. Following a similar pattern, we find that present-day radiometric imagery methods are based on techniques available from other disciplines, though they are not optimum from a radiometric standpoint.

Though the practical consideration of available capabilities may dictate, at least for the moment, the need for compromise, it appears in this case that there is no active plan to overcome these limitations which have imposed the compromised position. These limitations are not insurmountable - the recognition of their existence and the importance of a prompt solution is the first step.

The significance of the low frequency region and the need for more optimum methods of measurement leads to the following advanced technology requirements:

(1) More effective means for obtaining parametric displays from airborne platforms. In particular, techniques which eliminate the need for laborious off-line data reduction and provide more efficient use of aircraft flight time.

(2) More effective high speed imagery methods which provide improvement in angular resolution without degradation in sensitivity and include a real, or near real, time imagery readout.

(3) Simultaneous dual polarization image capability.

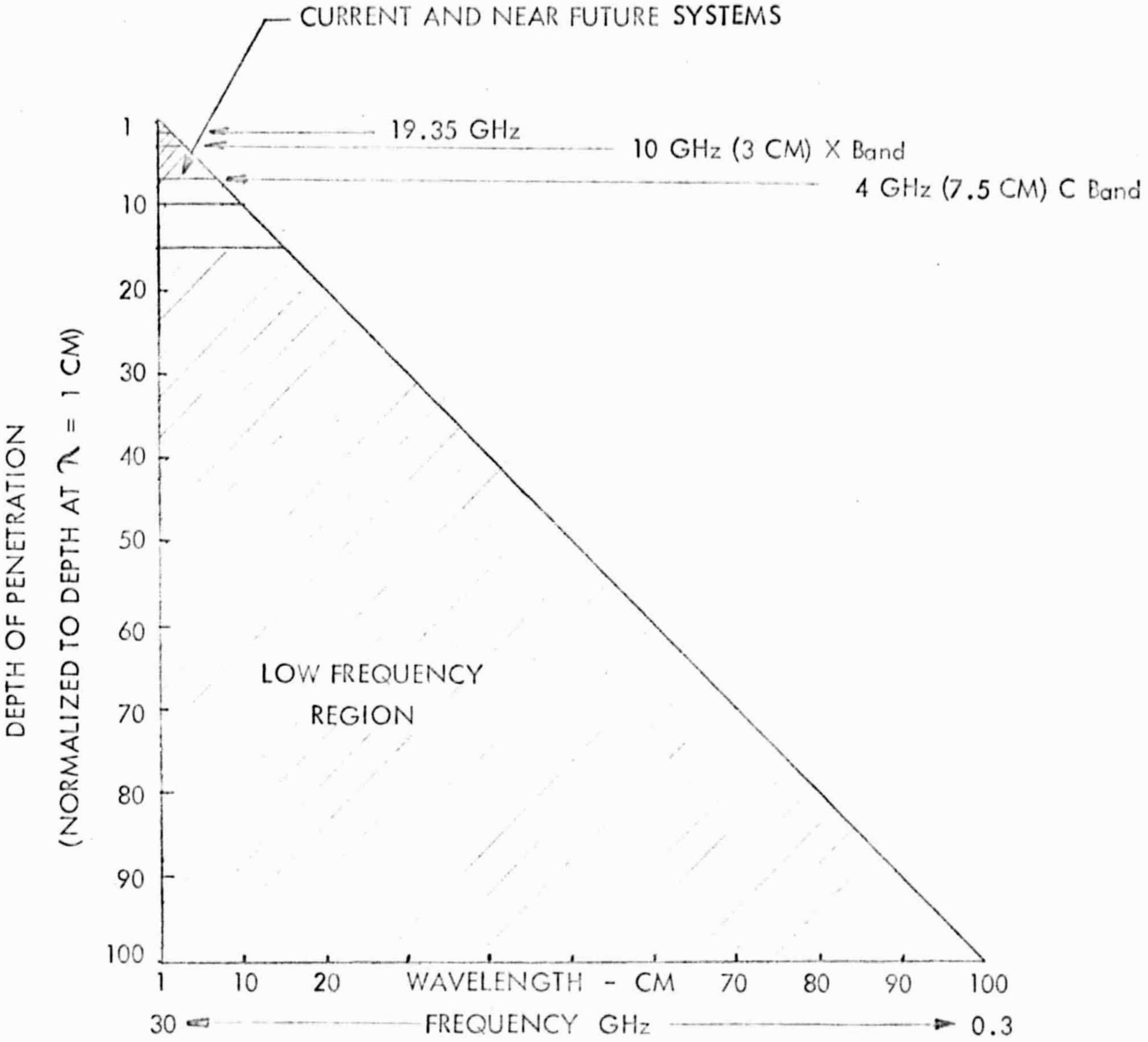
(4) Application of these measurement techniques to the exploitation of the low frequency region.

4.1 Significance of the Low Frequency Region

The most frequently mentioned advantage of microwave radiometric sensing is the ability to obtain thermal images of the terrain under overcast weather conditions that preclude infrared imaging. While this is generally true throughout the entire microwave frequency range, atmospheric effects are minimum at the low frequency end of the scale. Hence, an effective exploitation of this favorable characteristic should logically be concentrated in the low frequency region.

An equally important characteristic is that the observed microwave radiation originates below the surface of the material at a relative depth in near linear proportion to the wavelength of observation. This ability to "penetrate below the surface" is vitally important to most all earth resource applications. Simultaneous multiple wavelength observations would provide radio signature maps corresponding to several different depths of penetration below the surface boundary. This characteristic of microwave radiation from terrain materials is critically significant even under clear weather conditions. The application of this capability to related needs in the areas of hydrology, geology, and agriculture is immediately apparent when one considers that the depth of penetration at a wavelength of one meter (300 MHz) is nearly 100 times greater than the depth of penetration at a wavelength of one centimeter (30 GHz). Present and near-future aircraft imaging systems however cover the wavelength range from approximately 1.5 cm to 7.5 cm providing a relative depth of penetration of only 5 to 1. By exploiting the low frequency region, the available penetration depth would be increased by a factor of 13 over that currently planned at 7.5 cm, (See Figure 4-1). Typical User applications which would benefit from the increased depth of penetration offered by low frequency observations include determinations of:

(1) Soil moisture content in forest areas as an aid in evaluating the potential forest fire hazard in the particular areas.



RELATIVE DEPTH OF PENETRATION OF

MICROWAVES IN TERRAIN MATERIALS

FIGURE 4-1

(2) Relative soil moisture content among several areas fed by a common irrigation system in order that irrigation may be scheduled in the most efficient manner to provide maximum use of available water.

(3) Depth of the permafrost layer below the surface in arctic regions.

(4) Distribution of surface water beneath large storms, such as hurricanes, to determine the nature and extent of disaster areas.

(5) Relative ocean surface temperatures to map and observe the motion of thermal anomalies, such as the Gulf Stream, as an aid in correlating these features with fish movements.

(6) Depth and water content of snow areas as an aid in scheduling flood control activities.

(7) Heat budget of glaciers to improve water runoff prediction capability.

(8) Lines of demarcation between fresh and salt water as an aid in pollution studies.

Another important feature of microwave radiation from terrain materials is the relationship between surface roughness effects and the wavelength of observation. Surface roughness is a relative term, since the magnitude of its effect is determined by the amplitude distribution of the spatial geometry of the surface about a mean surface level, measured in units of wavelength. Some user applications require the determination of surface temperature, or relative surface temperature, whereas other require a discrimination between different surface, or subsurface, materials. Few User applications require a knowledge of the surface roughness; an obvious exception is sea state information for the oceanographer and the shipping industry. It is well known that the microwave emission of terrain materials is influenced by both the surface roughness and the temperature of the material; thus, it is desirable to be able to either separate the two effects or eliminate one of them. This again, dictates long wavelengths to minimize the roughness effects on a scale smaller than a wavelength.

These three characteristics - negligible atmospheric effects, depth of penetration, relative insensitivity to surface roughness - support the significance of the low frequency region for earth resource applications.

The actual depth of penetration for a particular wavelength of observation is extremely difficult to compute for other than simplified models, since the observed brightness temperature requires solution of the equation of radiative transfer which, in turn, requires knowledge of the time function of the temperature distribution with depth below the surface boundary. The temperature distribution with depth is obtained from the solution of the heat conduction equation for the material.

In general, the depth of penetration of the heat wave is determined by the density, specific heat, and thermal conductivity of the material. The temperature distribution within the material at any time is then determined by the interaction of these parameters on the intensity of the incoming flux incident at the surface boundary.

The outgoing electromagnetic radiation is determined both by the temperature distribution below the surface of the material, as well as the electrical properties of the material; in particular, the complex dielectric constant, dielectric conductivity, and magnetic permeability. A complete solution of the equation of radiative transfer is complicated by practical considerations such as spatial variations in the thermal, as well as electrical parameters, that are experienced in the real world.

It may be helpful here to review the general characteristics of the physical processes which give rise to microwave radiation from terrain materials.

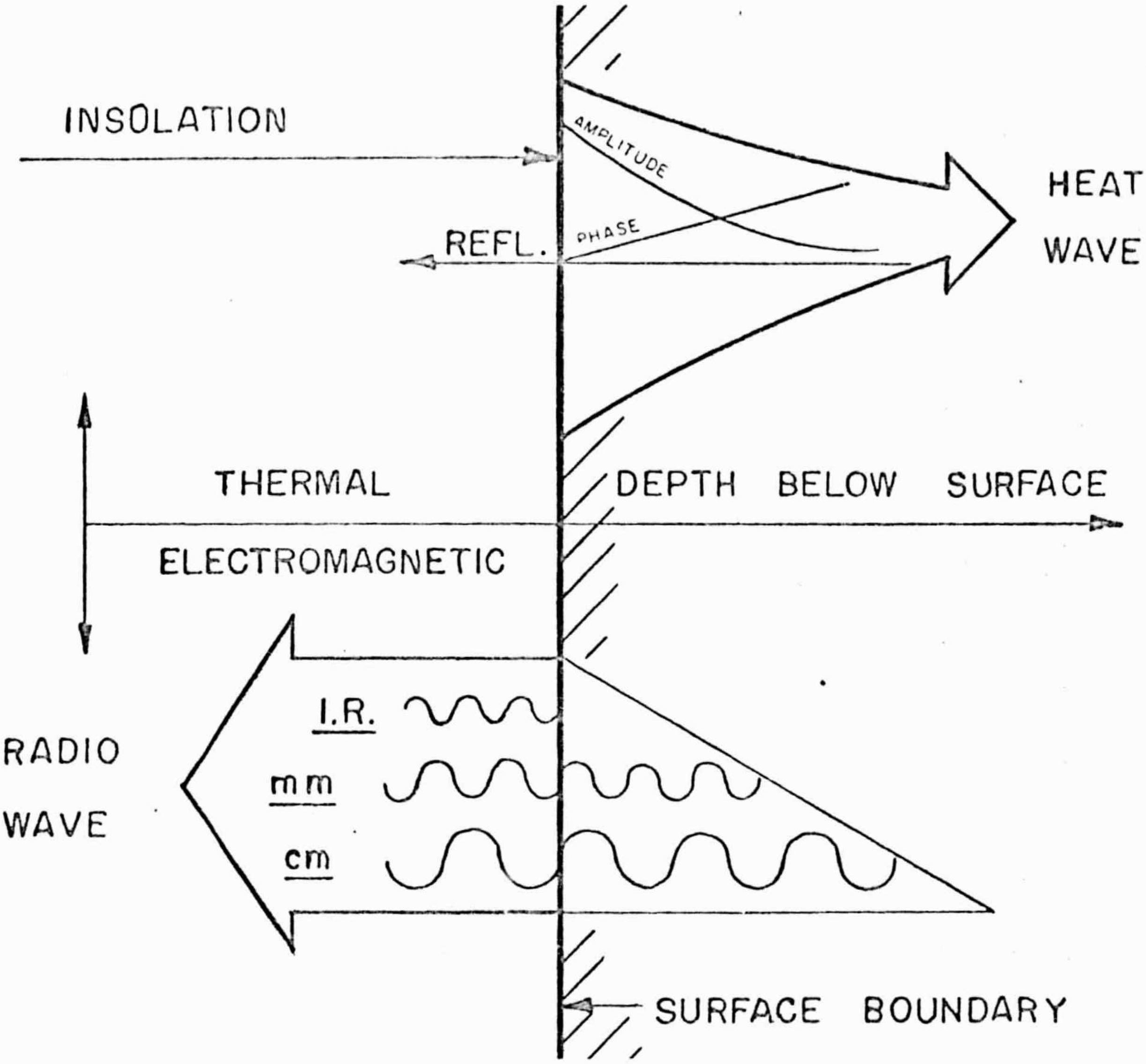
The solar radiation absorbed during the day-time propagates in the form of a "heat wave" into the subsurface in a manner determined by the thermal conductivity, specific heat, density and structure of the subsurface material.

The thermal properties, combined with the homogeneous, quasi-homogeneous or complex stratified nature of the subsurface material determine the propagation characteristics of the "heat wave." These subsurface conditions and material characteristics, in turn, affect the temperature variations observed at the surface. For example, a highly conducting (thermally) subsurface material would allow heat to be rapidly dissipated away from the surface into the interior of the material.

The physical processes which give rise to the observed radio brightness temperature are shown diagrammatically in Figure 4-2.

(a) The solar flux incident on the material surface is partially reflected; however, the majority of energy is absorbed by the surface. Some of the absorbed energy is propagated into the material in the form of a "heat wave." The thermal properties of the subsurface material determine the propagation characteristics of the "heat wave" and, in turn, determine the temperature distribution as a function of depth below the surface.

(b) The electromagnetic radiation at microwave wavelengths originates in the subsurface layers and is propagated toward and through the surface with an amplitude and phase determined by the electrical properties of the material and its temperature distribution with depth below the surface.



1. The characteristics of the Thermal Wave are determined by the thermal properties of the material.

2. The intensity and phase of the Electromagnetic Wave is determined by the amplitude and phase of the Temperature Wave with depth in the material and the electrical properties of the material.

PHYSICAL PROCESSES FOR DETERMINATION OF RADIO BRIGHTNESS TEMPERATURE

FIGURE 4-2

4.2 The Need for Optimum Methods of Measurement

As a result of this investigation, it was determined that passive microwave methods of measurement presently used in support of Earth Resource application studies are not optimum. They either fail to reflect an appreciation for the current role of measurements in the present exploratory phase, or employ instrumentation techniques which limit observational capabilities. Data requirements based on the role of present day measurements lead to the following significant conclusions:

(1) Ground based measurements are best suited to the longer term effort required to develop a comprehensive understanding of the physical processes associated with the thermal radiation characteristics of materials.

(2) Airborne and satellite observing platforms are most responsive to the immediate measurement data needs of the earth resource program; however:

- (a) Present methods for obtaining parametric displays from airborne platforms are exceedingly difficult to execute.
- (b) Present passive microwave imagery techniques based on single beam line scanning provide poor quality low speed images.

The Role of Measurement

The use of passive microwave sensing for Earth Resource applications is in an exploratory phase. The objective of supporting measurements is to determine those observed terrain material radiation characteristics which demonstrate a consistent relationship with specific material or material conditions. The material or material conditions of interest are those for which the available knowledge can be usefully applied by a User. There are two possible approaches to this investigation:

(1) Development of a detailed understanding of the inter-relationship of the physical processes which determine the observed radiation characteristics of materials for all combinations of significant parameters, followed by the derivation of anticipated radiation characteristics for the material conditions of interest to various Users.

(2) Direct measurement of the radiation characteristics of materials in their natural environment under known conditions leading to an empirical determination of the existence of consistent and useful relationships.

The latter approach is at first unpleasing to a physicist since it implies a solution based only on "hope". However, thorough and meaningful investigatary efforts logically begin with the planning of experiments which involve theory based on expectations, or "hope". The complexity of this particular problem is such that one working with it soon realizes that the development of a detailed understanding of the associated physical processes also requires an empirical approach. Since measurements are required in support of either approach, it is important to consider the measurement philosophy and associated techniques most likely to provide an efficient near future definition of useful applications for passive microwave sensors. It is important to note that a detailed understanding of the physical processes which determine the observed radiation characteristics of materials is not a prerequisite to establishing the usefulness of the observational data.

In our opinion, the second approach is more directly applicable to User requirements. This does not imply that a detailed understanding of the associated physical processes is unimportant and should not be pursued in paralled but rather that the time and level of effort needed appears inconsistent with current requirements.

The most effective role of measurements at this time is that which supports the empirical determination of relationships between observed radiation characteristics and material conditions which are consistent and useful. Useful, in this sense, implies data of value to the

User. It, therefore, implies a data form that can be obtained from a useful operational observing platform, and displayed in a format which is operationally adaptable to the User's methods for analysis as well as information distribution.

These requirements are imposed on those who design the experiments and perform the measurements. The responsibilities of the experimenters include not only the form of the data display but also the assurance that the data displays include significant parametric comparison, and further that the instrumentation methods used do not restrict the measurement capability to less than that achievable.

We have concluded from an anaylsis of present methods of measurements that an inadequate parametric comparison is provided. The most critical, least exploited, parameter is frequency. The low frequency region is essentially unexplored, though the increased depth of penetration, insensitivity to surface roughness and negligible atmospheric effect suggests substantial benefits might be realized for the majority of Earth Resource applications.

Analysis of present day aircraft imagery instrumentation methods indicates that these methods limit available sensitivity, angular resolution, and observing platform velocity to values significantly less than achievable. In addition, present methods for obtaining parametric displays from aircraft are both costly and extremely difficult to execute. The associated instrumentation methods and data reduction techniques presently in use are unnecessarily restrictive.

Present Methods of Measurement

Ground based measurements provide opportunities to develop a physical understanding of the radiation characteristics of materials under controlled conditions. A detailed physical understanding of the thermal radiation properties of materials requires a long term effort of analysis supported by measurements. The time scale for an investigation of this type appears to be inconsistent with the needs of the Earth Resource program. Ground based measurements have already made a major contribution in the sense that they have identified the sensor instrument variables which are important, such as frequency, look angle and two orthogonal polarizations. In addition, they have established the dynamic range of anticipated brightness temperatures for a wide variety of terrain materials.

Perhaps, the most significant contribution that can be made at this time through ground based measurements is the careful calibration of radiometric sensor systems, prior to their installation on airborne and spacecraft observing platforms. This problem has been partially solved by the recent invention of the absolute radiometric mode, which provides an output indication of the absolute temperature of the noise power at the terminals of an antenna system. The translation of this absolute temperature into its various contributing components, spatially distributed throughout the antenna pattern is the next and more difficult step. An empirical solution, using a carefully instrumented ground based "radiometric range," appears to be a potentially useful approach.

The Boom-Bin Concept

In this configuration, a multi-frequency radiometric sensor is supported on a horizontal boom. The boom is supported on a tower which moves in azimuth over earth installed bins filled with various materials or the same material with varying conditions, such as surface roughness or water content. This configuration is most pleasing to the physicist since it provides a nearly complete control of the experimental process. Measurements of this type contribute to an improved understanding of the physical processes associated with the thermal radiation characteristics of materials. However, they provide little useful information concerning the radiation characteristics of materials under natural environmental conditions. An instrument of this type located in Boston, for example, when equipped with bins of material selected from sites around the country would ultimately provide a measure of soil radiation characteristics when exposed to the Boston environment; e.g., "Kansas - Boston" wheat characteristics. It is apparent that the most appropriate bin materials for a measurement instrument of type would not necessarily be representative of any specific "User material," but rather representative of various chemical compositions and conditions suggested by an orderly investigation of the interplay of the parameters which enter into those processes which contribute to the thermal radiation from materials.

Mobile Ground Based Field Measurement Systems

The relocation of materials to their non-natural environment in the boom-bin configuration can presumably be overcome by locating the measurement system in the natural environment of the material to be investigated. Historically, the mobile van installation for field measurements of this type has been favored as a reasonable alternate to the fixed installation of an on-site tower and boom. The mobile van installation, however, suffers limitations imposed by the geometry of its configuration which contaminates the natural environment. A further significant limitation is the far field characteristic of the sensor antennas, particularly at the longer wavelengths, which requires that the antennas be located several hundred feet above the material sample to obtain a reasonable angular resolution. If the antennas are placed close to the material, the angular resolution must be proportionally reduced, thereby negating the significance of look angle as an important parameter. Either approach is severely limited when looking in the nadir direction. The instrument on the high tower observes part of the tower. The instrument on the boom extending from a van completely shadows the material from incoming atmospheric radiation in the zenith direction. Further, the van and boom act as a direct source of radiation on the material sample. A completely reflecting structure, for example, would emphasize reflection of the sky noise component in preferred directions determined by the geometry of the field installation. If the van installed boom or other portions of the measurement instrument were covered by absorbing material, then direct thermal radiation from the absorber would be incident on the source material under investigation.

Combination Aircraft and Ground Based Measurements

It has, on occasion, been suggested that aircraft measurements would be usefully supported by simultaneously obtained ground based radiometric measurements. The argument most frequently given in support of these combination measurements is calibration of the radio signal observed from the aircraft platform through use of the radio signal observed on the ground. This is not a technically sound argument for the following reasons:

(a) The radio signal incident on the aircraft installed sensor will differ only slightly from the radio signal viewed by a ground based terminal (assuming that the several geometrical factors noted above do not contaminate the ground based signal). The only difference between the two, assuming both observe the same material at the same angle, frequency, polarization, etc., will be the attenuation of the signal by the intervening atmospheric path and the reradiation outward from the atmosphere to the aircraft installed sensor.

(b) From the foregoing, it would appear that combination measurements of this type are useful in determining atmospheric effects. However, in an operational system, sensing of atmospheric conditions and prediction of anticipated effects on the radio signal received from the terrain must be accomplished with sensors located on the observing platform.

One concludes from the foregoing that combination aircraft and ground based measurements are not required if aircraft installed sensor systems are carefully calibrated. The question is whether combination measurements represent the optimum approach for calibration of aircraft installed systems. It would appear more logical to calibrate the aircraft sensor on a ground based radiometric test range prior to installation on the aircraft. The test range in this case would be equipped with materials of known thermal radiation characteristics not necessarily related to any specific material whose characteristics are to be investigated.

Ground Based Measurements at Long Wavelengths

The foregoing discussion concerning the role of ground based measurements for Earth Resource applications is, in general, applicable to the entire microwave and millimeter range of interest. A relatively simple geometrical analysis of restraints imposed on ground based measurements in the low frequency region quickly exposes limitations that make ground based measurements at long wavelengths unfeasible. We need only recall that ground based measurements lead to a parametric display of brightness temperature as a function of look angle in two orthogonal polarizations. As previously noted, the significance of look angle is related to the size of the antenna beam angle. The largest useful beam angle required to obtain a significant number of discrete look angles is of the order of 1/10 radian (approximately 6°). At the longest wavelength of interest (1 meter), the antenna aperture diameter to obtain a beam angle of 1/10 radian is 10 meters. The far field of an antenna of this size when operating at a wavelength of 1 meter is nearly 1/4 km, or approximately 700 feet. This means that the antenna must be located on a tower at least 700 feet high. If an antenna with a 1/10 radian beam angle were located on such a tower and pointed in the nadir direction, the beam angle projection on the ground would be approximately 70 feet in diameter. In order to minimize observation of the tower in the sidelobe structure of the antenna when the antenna is pointed in the nadir direction, it would be necessary to support the antenna on a horizontal boom extending out from the tower at a distance of at least 3 beam angle projections (210 feet).

From the foregoing analysis, it is apparent that the tower and boom dimensions are inconsistent with the capabilities of a simple mobile van installation. Though these dimensions might be accomodated in a fixed boom-bin type installation, there is little direct immediate value to be obtained from a measurement configuration of this type for the various reasons previously described.

One also concludes from the foregoing analysis that very little, if any, parametric analysis of terrain material characteristics has been accomplished through ground based measurements in the low frequency region. An instrument configuration of this type would certainly have attracted publication in the literature.

Man-made RFI

Man-made radio frequency interference is of greater concern in the low frequency region than at high frequencies. Man's exploitation of the frequency spectrum has historically progressed from lower to higher frequencies. Frequencies in the range from 300 MHz to 2 GHz have been assigned to a variety of communication and radar system applications. Fortunately, there are several radio astronomy bands in this low frequency region. These "quiet bands" have been established through international agreement. No transmitters are allowed in these bands, consequently, they are obvious candidates for application to passive remote sensing. The presently available radio astronomy bands from 300 MHz to 38 GHz are listed in Table 4-1.

TABLE 4-1

RADIO ASTRONOMY FREQUENCIES

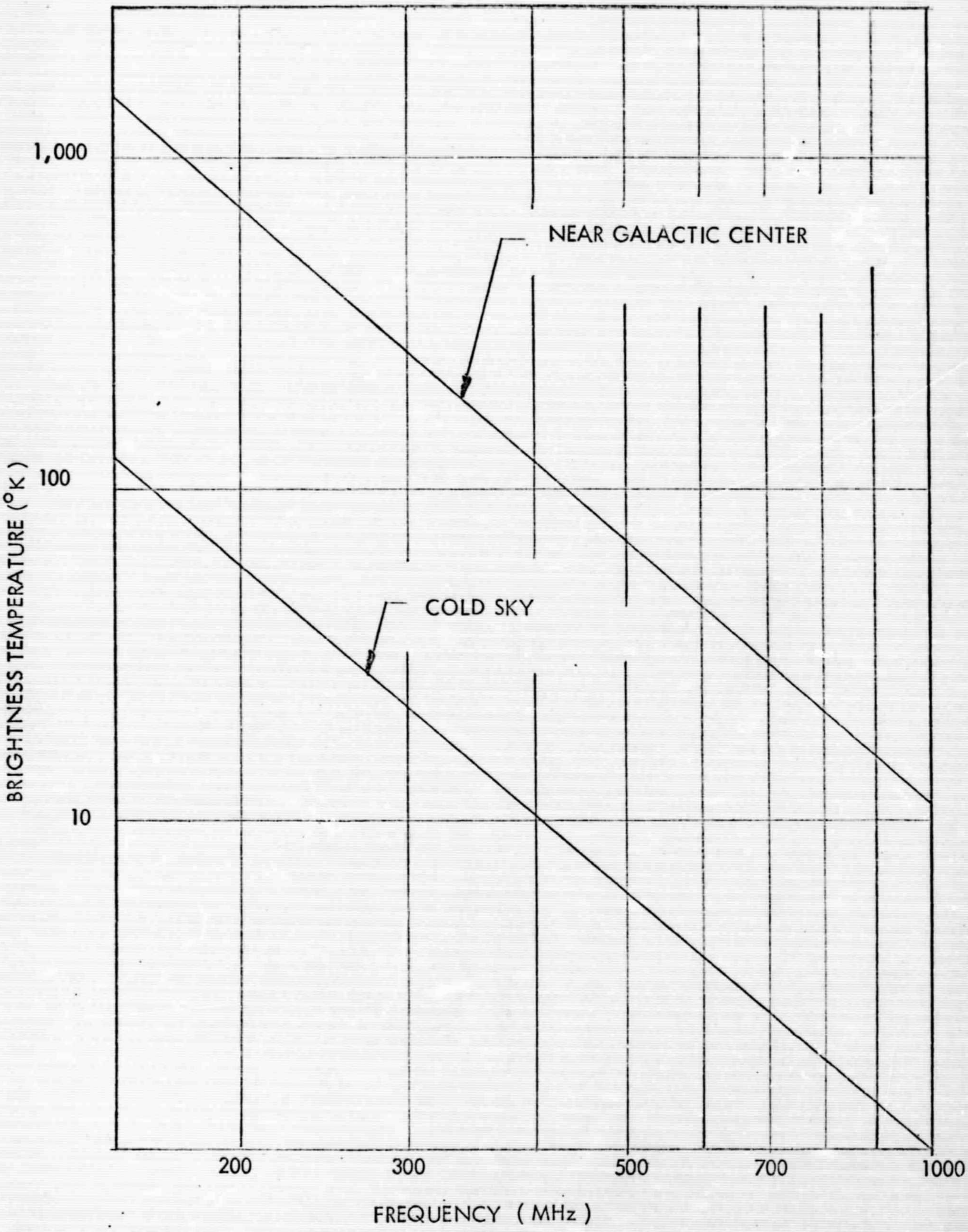
322 - 329 MHz	5800 - 5815 MHz
404 - 410 MHz	8680 - 8700 MHz
606 - 614 MHz	10.68 - 10.7 GHz
1400 - 1427 MHz	15.35 - 15.4 GHz
1660 - 1690 MHz	19.3 - 19.4 GHz
2690 - 2700 MHz	31.3 - 31.5 GHz
3165 - 3195 MHz	33.0 - 33.4 GHz
4800 - 4810 MHz	33.4 - 34 GHz
4990 - 5000 MHz	36.5 - 37.5 GHz

It is unfortunate that some of the assigned bands are so narrow since radiometric sensitivity improves directly as the square-root of bandwidth. The number of bands assigned in the low frequency region, however, is more than adequate to obtain a significant number of quantitized steps to capitalize on the wavelength dependence of penetration depth. An optimum approach to system design would be predicated on operation within the radio astronomy bands. Systems should be equipped with a dual predetection bandwidth capability; one determined by a predetection filter with steep skirt selection confined to the radio astronomy band, and a second filter somewhat broader than the assigned band but centered on the band center frequency. The broader band would be useful in remote areas away from the congestion of large city communication traffic. A relatively simple threshold logic circuit would implement the automatic selection of the most appropriate operating band.

Cosmic Noise

The microwave window centered at a wavelength of 7.5 cm is bounded at high frequencies by atmospheric attenuation and at low frequencies by cosmic noise. At frequencies below 300 MHz, the cosmic noise intensity expressed in effective brightness temperature units rapidly exceeds the earth ambient temperature of 290°K. The intensity of this noise field must be carefully considered in the design of low frequency antenna systems for Earth Resource applications to minimize back and far-out sidelobe contributions. Another effect, which has not been reported to our knowledge but undoubtedly would be observed, is a marked increase in the brightness temperature of the sea at observing frequencies lower than 100 MHz. At these frequencies, the cosmic noise is so intense that the reflected component from the sea surface would exceed the nominal earth ambient temperature of 290°K. At these frequencies, the temperature contrast between sea and adjoining land would be the reverse of that observed at short wavelengths; i.e., the sea would appear "hot" and the land "cold". A possible application might take the form of a bistatic scatterometer using cosmic noise as the "transmitter".

A graphical plot of the frequency dependence of cosmic noise in effective brightness temperature units is shown in Figure 4-3.



GALACTIC NOISE BACKGROUND

FIGURE 4-3

Parametric and Image Displays from Airborne Platforms

There are two types of passive microwave sensors presently used in aircraft measurement programs:

(1) Mechanically adjusted, single polarization, and pointing quantitized spot analyzer to obtain a parametric display.

(2) Single polarization, single beam scanning system to obtain an image display.

A quantized spot analyzer is depicted in Figure 4-4. The sensor operates simultaneously, at several frequencies with the individual antenna aperture diameters selected to provide the same antenna beam angle along a common boresight. Each antenna is linearly polarized. Reception at an orthogonal polarization is accomplished by mechanically rotating the antenna structure through an angle of 90° in the plane normal to the boresight axis. The look angle, relative to the nadir direction, is also mechanically adjusted.

The complexity associated with data accumulation and reduction for a system of this type, is quickly grasped when one recalls that the objective is to provide a parametric display of brightness temperature as a function of look angle for two polarizations (usually vertical and horizontal.) The pictorial presentation in Figure 4-4 shows one possible mode of operation. At the initial position of the aircraft, the look angle is adjusted to project the antenna beams on the terrain material to be analyzed. The look angle is set at the maximum angle that will be included in the final output display. As the aircraft moves along the ground track, the look angle is continuously adjusted so that the selected terrain sample is maintained in the antenna beams until the sample is in the nadir direction. This provides the data required to develop a parametric display of brightness temperature as a function of look angle for one polarization. To obtain the parametric display in the orthogonal polarization, the aircraft must perform a circular maneuver to re-acquire the material sample on the

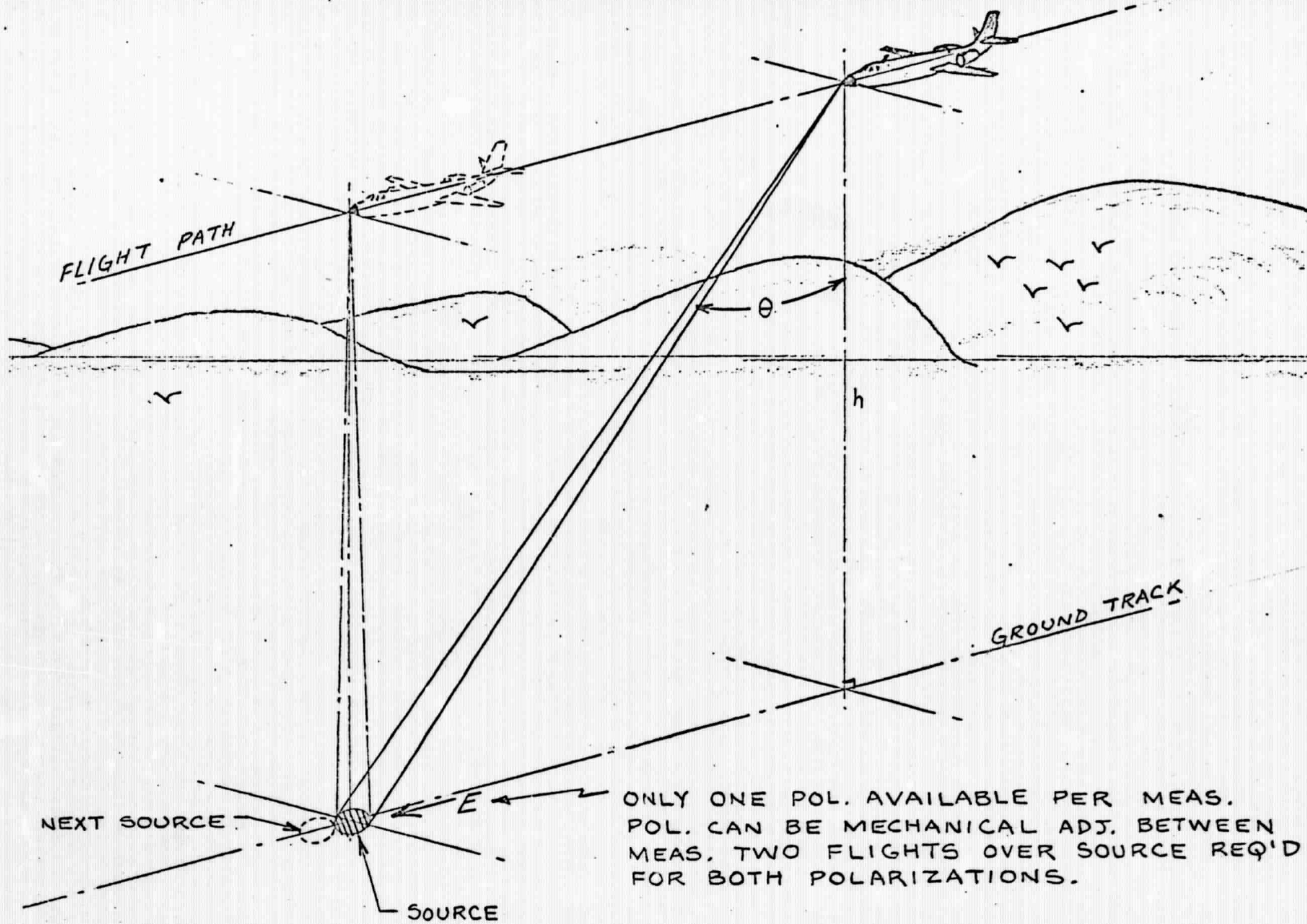


FIGURE 4-4 - QUANTIZED SPOT ANALYZER (MECHANICALLY ADJUSTED, ONE POLARIZATION AND POINTING) original ground track, and then it must re-fly the ground track. The entire flight sequence provides the data required to generate the parametric display of brightness temperature versus look angle in both polarizations, for the one discrete sample originally selected. The entire sequence must then be repeated to obtain a parametric display of the next sample. Aside from the attendant difficulties of precisely re-flying the same ground track and continuously adjusting the look angle in synchronism with the ground track velocity, the entire procedure is very time consuming since most of the aircraft flight time is devoted to the turn-about reacquisition maneuver.

The most commonly used method represents a slight modification of the previously described procedure. The procedure, in this case, is to set the look angle at the maximum value to be used in the final parametric display, and then proceed to fly along a pre-selected ground track. The data accumulated in one flight along the ground track is the brightness temperature as a function of time for a fixed look angle and polarization. In the data reduction process, time - through the knowledge of aircraft ground speed - is converted to an identification of the material sample in the antenna beam at each interval of time. Each flight along the ground track, therefore, provides one point on the desired parametric display for any one material sample; i.e., brightness temperature as a function of one look angle and one polarization. The ground track is then successively re-flown for each of the required incremental changes in the look angle needed to develop a complete parametric display for one polarization. The entire series is then re-flown to obtain the data required for the second polarization.

As a typical example of the number of successive flights over a selected ground track required to develop a parametric display, consider the case of a 3° beam angle covering a look angle range from nadir to 60°. A minimum of 20 incremental look angle steps will be required for each polarization or a total of 40 flights over the identical ground track. Here again, most of the aircraft time is devoted to the turn-around acquisition maneuver. In addition, the data reduction process becomes quite complex and tedious. This can be seen by recalling that the data required to obtain a complete parametric display for any selected sample of terrain material along the ground track will be contained in all 40 data records, since each record contributes one data point to the final display. Each segment of the magnetic tape recording, corresponding to each flight along the ground track, must be separately analyzed to determine the location of each material sample through knowledge of the speed along the ground track and a synchronizing time pulse on the tape. Deviations in the ground speed among the 40 data records further complicates the data reduction process.

Aside from the fortitude required of the investigator, particularly in the data reduction process, the principal drawback is the large amount of time needed to accumulate the required data - at minimum, several hours, and on some occasions several days - with the result that the observing conditions and the conditions of the material sample may change during the time required for the accumulation of a complete set of observational data.

Parametric displays are very important since they most closely complement the data form obtained from ground based measurements. Their usefulness in the interpretation of image displays is equally significant.

Image displays have become increasingly popular in recent years. The reason is not immediately obvious when one notes that each terrain material sample displayed on an image provides a measure of brightness temperature at only one look angle and with present instrumentation, at only one polarization and one frequency. The most significant observing parameters are frequency, look angle, and two polarizations. Substantial theoretical as well as ground based measurement efforts have been devoted to establishing the relationships between these various parameters for various materials and material conditions.

It is difficult at first to perceive the value of a data form (image) which precludes interpretation in terms of these well-known parametric relationships. The development of a parametric display using an imaging system, however, would be nearly as complex as the methods associated with the previously described quantized spot analyzer. In order to obtain look angle information, several images of the same area would be required; each obtained by successive displacement of parallel ground tracks, separated by the antenna beam projection in the nadir direction. Present day imaging sensors which are equipped with a single polarization capability would be unable, by any aircraft maneuver, to obtain data required for a parametric display of the orthogonal polarization.

It is apparent from the foregoing discussion that present day passive microwave images are not susceptible to interpretation in the normal parametric sense. Correlation of the observed signal characteristics with known material and material conditions represents the only available avenue for analysis of a single image. Temporal variations are, of course, susceptible to analysis on an image-to-image basis.

The foregoing comments concerning the restraint on look angle as a useful parameter for data interpretation of an image do not apply, of course, in the case where the sample under observation is uniformly distributed throughout the entire image. A typical example would be the observation of sea state on an image display.

The popularity of image displays is based on User preference. This data form does, in most cases, meet the User's needs for operational adaptability; i.e., usage.

The imaging sensor configuration in common use today is shown pictorially in Figure 4-5. A single antenna beam is either step-scanned or continuously scanned normal to the ground track through an angular extent determined by the desired maximum look angle of observation. The forward motion of the aircraft along the ground track produces a raster scan of the terrain. The principle disadvantage of this method is the restraint imposed on the available observing time for each independent sample. The total antenna beam scan time must be equally shared by each independent look angle increment. For a $\pm 50^{\circ}$ scan angle about the nadir direction, a sensor with a 3° beam angle is allowed to look only 1/33 of the time at each discrete sample contained in a line scan, in comparison with the time that would be

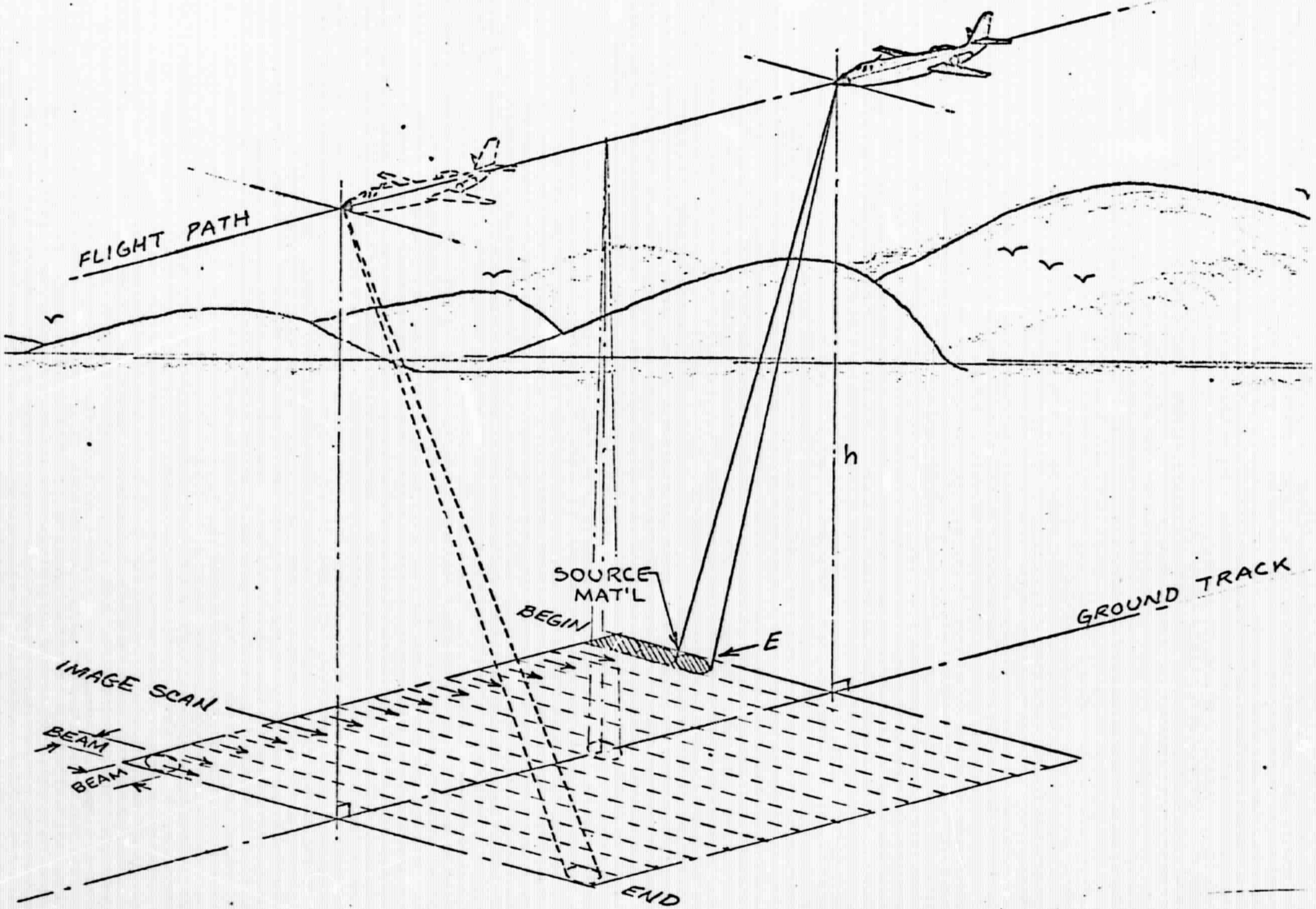


FIGURE 4-5 ONE POLARIZATION, SINGLE BEAM, SCANNING IMAGER

available to a quantized spot analyzer with the same size beam angle pointing continuously in the nadir direction. The minimum detectable signal capability of otherwise identical systems would be a factor of 5.5 times poorer in the single beam scan-imaging mode.

4.3 Analysis of Instrument Technology Requirements

Restraints

Identification of airborne observing platforms as an effective means for data accumulation leads to consideration of the restraints these platforms impose on the design and performance characteristics of passive microwave sensors. These include:

(1) The physical size of the antenna structure and its effect on the aerodynamic characteristics of the aircraft.

(2) The velocity-height profile characteristics of the aircraft.

In planning an airborne measurement program, one of the first considerations is the desired projection of the antenna beam on the earth terrain. The antenna beam projection is determined by the flight altitude and the antenna beam angle, in particular:

$$\text{Beam Projection} = h\Theta_A \tag{4-1}$$

where the beam angle Θ_A is expressed in radians and the flight altitude h in a convenient linear dimension.

The size of the antenna aperture required to obtain the desired beam angle is determined by the wavelength of observation. The relationship is:

$$\Theta_A \cong \frac{\lambda}{D} \quad \text{(radians)} \tag{4-2}$$

where λ is the wavelength of observation and D is the antenna diameter required to obtain a beam angle Θ_A.

A comparison of antenna aperture diameters required to obtain a beam angle of 1/10 radian (approximately 6°) as a function of the wavelength of observation in the range from 1 cm to 1 meter is shown in Table 4-2.

TABLE 4-2

Antenna Diameter, D, vs Wavelength, λ , for a Beam Angle of 1/10 radian

λ(cm)	ν(GHz)	D (M)
1	30	0.1
3	10	0.3
10	3	1.0
15	2	1.5
20	1.5	2.0
50	0.6	5.0
100	0.3	10.0

If the angular resolution requirement were increased to 3° (1/20 radian), the antenna diameter requirements shown in Table 4-2 would be a factor of 2 larger at each wavelength. This is not a particularly severe requirement at a wavelength of 1 cm (frequency of 30 GHz) since the required antenna diameter would be approximately 8 inches. The antenna diameter required at 300 MHz, however, to achieve the same angular resolution (1/20 radian) would be in excess of 60 feet. From this simple example, the incompatibility of antenna size requirements and airborne observing platform capabilities becomes readily apparent.

Since the projection of the antenna beam on the terrain is a prime requirement for most measurement programs, one might consider than an obvious solution would be to fly at low altitudes and achieve the desired projection on the earth terrain with a larger beam angle and consequent smaller antenna aperture diameter. Unfortunately, this approach has two adverse effects:

(1) The beam angle size becomes so large that the received radiation represents an integrated composite over a large look angle extent about the nadir direction.

(2) The ability to obtain an image display is negated by the inadequate number of independent look angle samples available normal to the aircraft ground track; i.e., the significance of independent look angle samples is directly related to the size of the antenna beam angle.

Since image displays, as well as parametric displays, are required from airborne platforms, it immediately follows that an antenna beam angle of 1/10 radian is near the maximum useful value. Consequently, the minimum antenna size requirements for the low frequency region fall in the range of 1.5 to 10 meters in diameter, as shown in Table 4-2. Clearly, these size requirements, particularly at the longest wavelength, represent a significant mechanical interface consideration for present-day jet and most piston type aircraft observing platforms. It is important to note, however, that these size requirements are not unreasonable in terms of future satellite systems. Space-qualified 10 meter diameter antennas are today considered representative of the state-of-the-art. It is equally important to note that the mechanical tolerances imposed on antenna structures at long wavelengths are linearly less stringent than at short wavelengths, since the mechanical tolerance requirements for antenna structures are expressed in terms of a fixed fraction of the operating wavelength (usually 1/16).

It is apparent from the foregoing discussion that future earth-orbiting satellite systems will be capable of easily accommodating antenna size requirements even at the longest wavelengths in the low frequency region. A space antenna, 100 meters in diameter with a mechanical tolerance of 6 cm across the entire aperture, is certainly within the grasp of our near-future technology. An antenna of this diameter would provide a 0.6° antenna beam at the longest useful wavelength in the low frequency region.

Exploitation of the low frequency region is at present limited by aircraft capabilities. These restraints however will not be encountered in satellite systems. Measurements obtained from an airborne platform represent a useful step in satellite sensor system development. Airborne observing platforms such as blimps and helicopters are better suited to low frequency system requirements than typical winged aircraft, piston or jet.

A further significant area of consideration is the relationship between the minimum detectable signal capability, antenna beam projection, and velocity of the airborne platform.

If we assume that the system noise temperature and predetection bandwidth have been optimized and are fixed, the minimum detectable signal capability of a radiometric receiver is determined by the post detection integration time constant. For the simple case in which a single antenna beam is fixed and pointed in the nadir direction, the velocity of the aircraft determines the "sample time," defined as the elapsed time between two adjacent and tangential beam projections. The expression for the "sample time," t_s, takes the form:

$$t_s = \frac{h \Theta_A}{v} \tag{4-3}$$

where v is the velocity of the aircraft along the ground track.

In order to provide an independent measure of successive tangential beam projection samples, the nominal post detection integration time constant of the receiver should be approximately one-third of the sample time; i.e., the time that any portion of an independent sample remains within the antenna beam projection. The post detection integration time constant of the receiver, therefore, may be expressed in the form:

$$\tau = \frac{t_s}{3} = \frac{h \Theta_A}{3 v} \tag{4-4}$$

The sensitivity of a microwave radiometric receiver, expressed in terms of the minimum detectable root mean-square antenna temperature change, is inversely proportional to the square-root of the post detection integration time constant, i.e.:

$$\overline{\Delta T}_{rms} \propto \frac{1}{\sqrt{\tau}} \tag{4-5}$$

The following conclusions can be drawn from the relationships shown in Equations (4-4) and (4-5):

(a) For a fixed aircraft velocity and antenna beam angle, the sample time increases linearly with altitude; and hence, the available radiometric sensitivity increases as the square-root of the altitude.

(b) For a fixed altitude and aircraft velocity, the sample time increases linearly with the beam angle projection; and hence, the sensitivity improves with the square-root of the beam angle projection.

(c) Since the beam angle for a fixed wavelength of operation is inversely proportional to the antenna diameter, the radiometric sensitivity of the system will improve as the inverse square-root of the antenna diameter.

(d) To maintain the sample time constant for a fixed beam angle, a constant value of the ratio h/v is required.

These simple relationships show why passive microwave measurements from aircraft require lower speeds at lower altitudes in order to maintain a constant sensitivity. This is frequently referred to as the "low/slow — high/fast" condition. The relationships also show why the antenna beam angle cannot be made arbitrarily small, since improvement in angular resolution (reduction in beam angle projection) degrades the minimum detectable signal capability; i.e., the minimum detectable signal capability degrades as the square-root of the improvement in beam angle resolution.

From the foregoing, one reaches the interesting conclusion that the size of airborne antennas at short wavelengths are determined by the relationship between the minimum detectable signal capability and the velocity-altitude profile of the airborne platform. At longer wavelengths, typical of the low frequency region, the size of the antenna is determined by mechanical interfaces between the aircraft and the antenna structure, since at low frequencies one never reaches the condition where the beam angle is small enough to adversely affect the desired minimum detectable signal capability.

An example of these limiting conditions can be seen by referring again to Table 4-2. This Table lists the antenna diameters for selected wavelengths of observation which provide a 1/10 radian beam angle (approximately 6°). Note that a 30 GHz antenna is only 0.1 meter in diameter, while a 300 MHz antenna is 10 meters in diameter.

Assuming that the maximum antenna size for most piston and jet-type aircraft is 2 meters in diameter, and further recalling that present day radiometric sensitivity is essentially independent of frequency, in the frequency range from 300 MHz to 30 GHz, we note in reference to Table 4-2 that the 1 GHz antenna system is the largest (2 meters in diameter) that can be conveniently carried on an aircraft. If now we were to increase the diameter of a 30 GHz system from 0.1 meter to the allowed 2 meters and install it on the same aircraft with a 1 GHz system, the beam angle projection at 30 GHz would be decreased by a factor of 20. This would require a corresponding reduction in the post detection integration time by a factor of 20, leading to a degradation in sensitivity at 30 GHz by a factor of approximately 4.5. If now we installed a 300 MHz system on the same aircraft and reduced the antenna aperture diameter from 10 meters to 2 meters, this would result in a corresponding increase in the antenna beam angle from 6° to 30°. The integration time constant could then be increased by a corresponding factor of 5. The minimum detectable signal capability at 300 MHz would consequently be improved by a factor of approximately 2.25 over that obtained by the 1 GHz system.

The inescapable conclusion is that the characteristics of airborne observing platforms intimately affect both the spatial resolution and minimum detectable signal capability of passive microwave radiometric sensors.

In the foregoing analysis, we treated the case of a single antenna fixed in position and pointing in the nadir direction. However, there are several significant implications concerning methods for implementing imaging sensors on aircraft platforms that can be derived from the foregoing discussion.

The common present day technique for developing a microwave radiometric image is to step-scan the antenna beam of a single sensor in the plane normal to the aircraft ground track. By this technique, one scan of the antenna beam between pre-set look angles, equally displaced about the nadir direction normal to the flight path, must be accomplished in the previously defined "sample time." This assures that the succeeding line scan is appropriately interlaced to produce the desired image. In this case, the previously defined sample time for the fixed nadir looking system is now equivalent to the total scan time. Since the antenna beam must look at N independent samples in each line scan (where N is the total scan angle divided by the antenna beam angle), then the observing time for each look angle sample is 1/N of the sample time available for the case of a fixed signal capability for the scanning system is $\sqrt{N}$ poorer than the sensitivity of the nadir looking system. For example, a system with a nominal 3° beam angle when scanned $\pm 50^\circ$ about the nadir direction to produce an image must look at a minimum of 33 discrete samples in each line scan. The post detection integration time constant must, therefore, be reduced by a factor of 33 over that allowed if the beam were fixed and pointed in the nadir direction. The sensitivity in the scanning mode will, therefore, be a factor of 5.7 or approximately 7.6 db poorer than the minimum detectable signal capability of a fixed nadir looking system.

Imagery obtained by scanning of a single antenna beam introduces more significant limitations on system performance capability than those associated with aircraft velocity-height profiles. More optimum methods for obtaining passive microwave images are clearly indicated.

Potential Solutions

One possible solution to the degradation in sensitivity associated with the imaging mode is shown pictorially in Figure 4-6. The sensor system projects several simultaneous contiguous beams along a line normal to the ground track. In comparison with the previously described single beam scanner, 33 separate antenna beams would be simultaneously projected along the line normal to the ground track previously scanned by the single beam. One possible

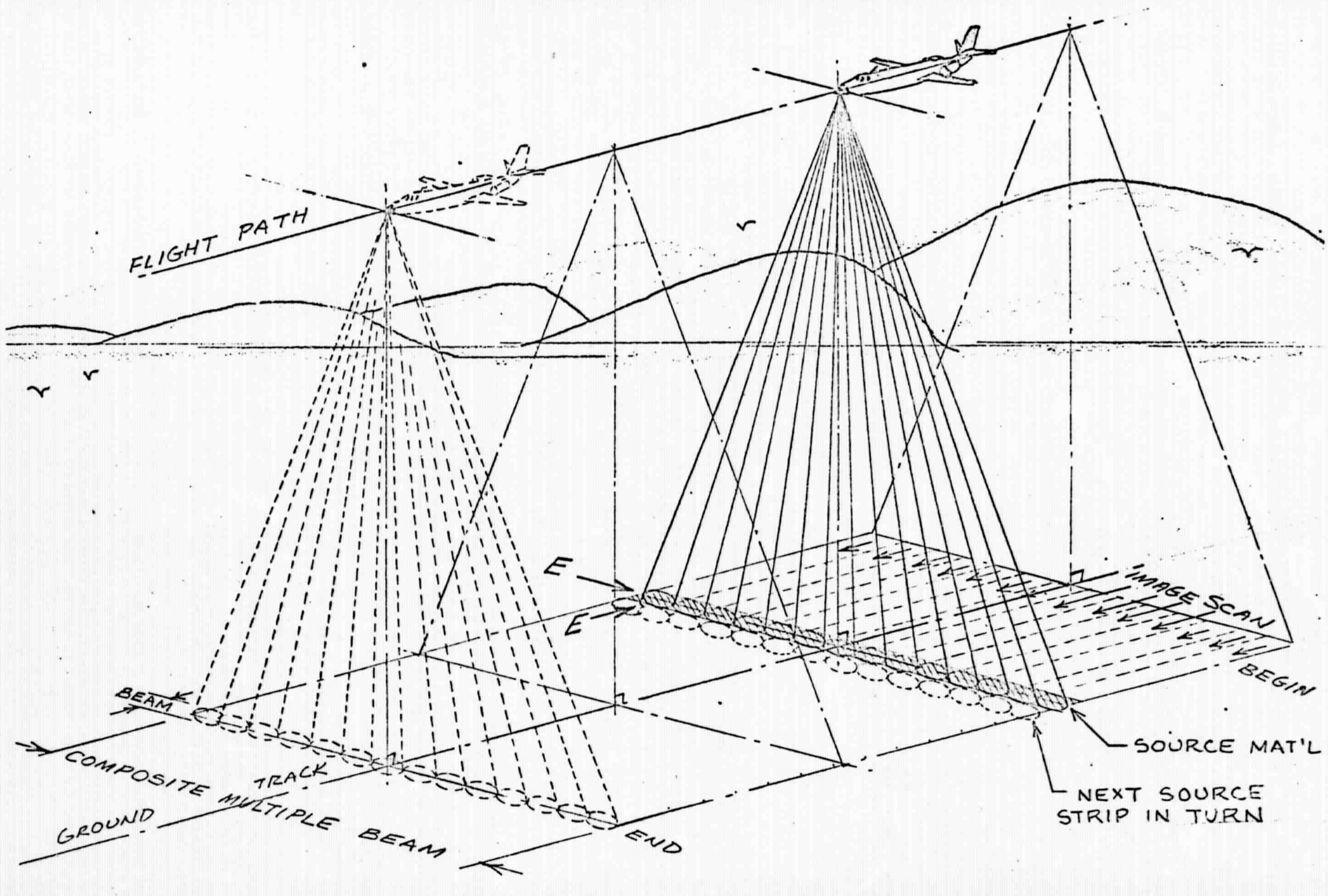


FIGURE 4-6 SIMULTANEOUS, MULTIPLE BEAM, DUAL POLARIZATION, CONTINUOUS STRIP IMAGER

means for implementing a multiple beam configuration of this type would take the form of a Luneberg lens fed by 33 individual in-line feed elements. The use of individual feed elements can easily be adapted to simultaneously sense the received radiation in two orthogonal polarizations. Each antenna feed element (or antenna beam direction) would be equipped with a microwave sensor. A system of this type would provide the following unique capabilities:

(1) A $\sqrt{N}$ improvement in sensitivity over that of a single beam scanner, where N is the number of discrete look angle samples. (In the case previously described, the improvement in sensitivity would be the $\sqrt{33}$ or a factor of 5.7).

(2) If the same sensitivity achieved by a single beam scanner is considered adequate, then the image could be obtained at aircraft velocities N times greater than available for a single beam scanner. In the example cited, this approaches satellite velocities at aircraft altitudes, or in the more practical case, the same beam angle projection (not beam angle) from satellite orbit as obtained at aircraft altitudes.

(3) Simultaneous images are obtained in two polarizations.

Parametric Displays from Aircraft

Another very unique feature associated with the simultaneous multiple beam, dual polarization, continuous strip imager can be obtained by rotating the system through 90° about the nadir direction so that the line of centers of the multiple beams fall along the ground track. In this configuration, the system becomes a multiple beam, dual polarization, continuous spot analyzer, as shown pictorially in Figure 4-7. Only one-half of the multiple beam structure, extending forward in one direction from the nadir position, is shown in Figure 4-7.

As the aircraft flies along the ground track, each sample of material resolved by

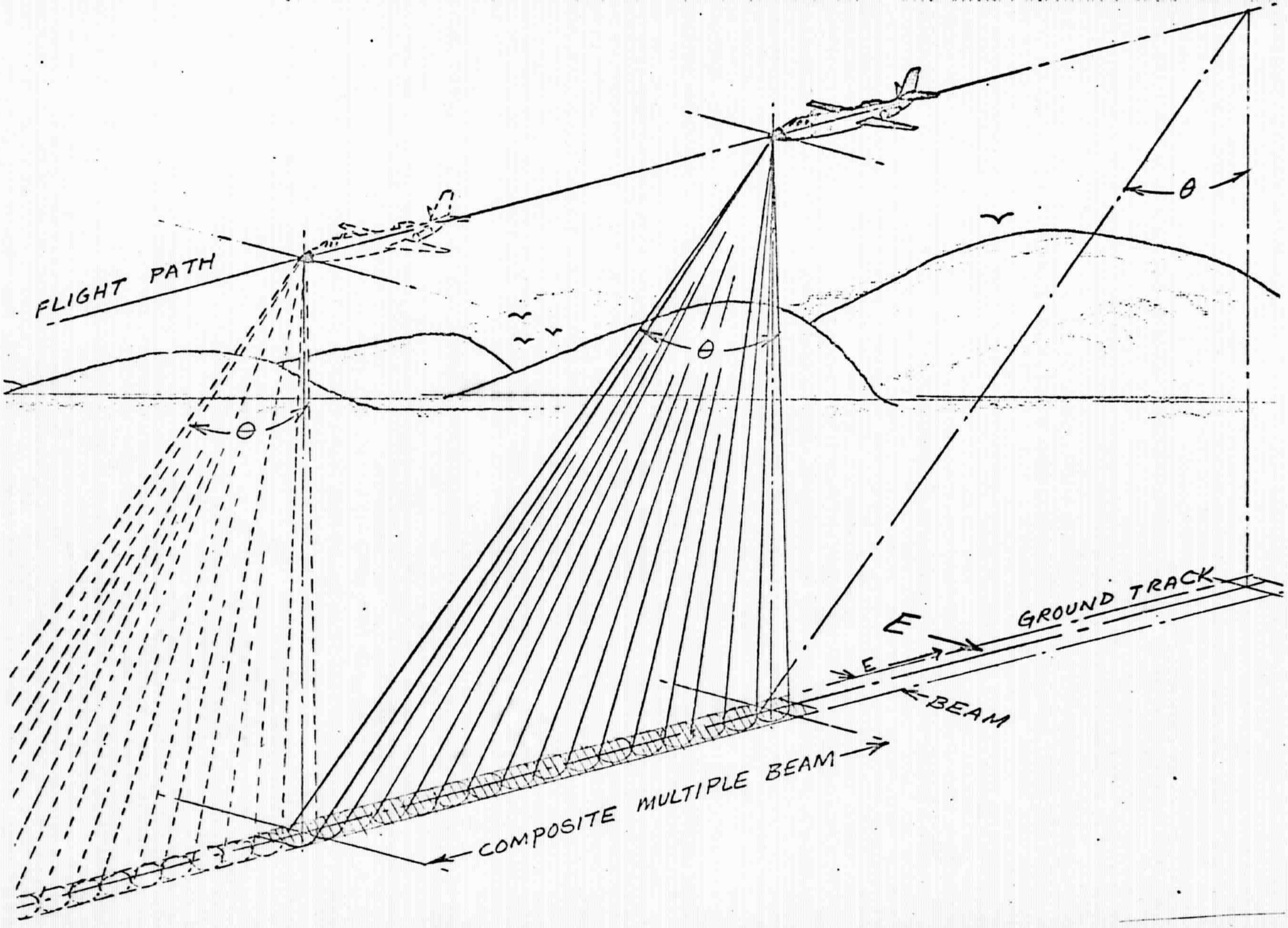


FIGURE 4-7   MULTIPLE BEAM, DUAL POLARIZATION, CONTINUOUS SPOT ANALYZER

the antenna beams moves through each beam in succession from the maximum look angle direction to the nadir direction. One flight along the ground track is all that is required to obtain real time parametric displays as a function of look angle in both polarizations for each contiguous sample of terrain material located on the ground track. No turn-about or reacquisition maneuver is required by the aircraft.

Advantages afforded by a system of this type, operating in either the parametric display or image display mode, are the high speed, high resolution capabilities that are obtained with an actual decrease in the off-line data reduction time requirements. The ability to obtain high speed real time parametric displays is particularly significant since this offers the opportunity to accumulate parametric data in a storage bank format which can be used for direct interpretation of image anomalies.

5.0 RECOMMENDATIONS

An experimental investigation of the potential benefit of long wavelength passive remote sensing to Earth Resource applications is suggested as an immediately significant technical objective. The effort requires the development and evaluation of remote sensing techniques applicable to aircraft and satellite observing platforms, which offer substantial improvement over present methods. Emphasis should be given to those techniques which will provide:

- Simultaneous dual polarization images;
- Simultaneous dual polarization parametric displays;
- Improvement of $\sqrt{N}$ in image sensitivity or N in observing platform velocity where N is the number of antenna beam directions normal to the vehicle ground track required to develop an image.

5.1 User Involvement

A more effective organization and implementation of measurement programs (extending beyond technical detail) is of critical concern. It is clear that these programs must be organized to provide a far better coupling of interdisciplinary relationships than typically achieved thus far. Seminars have been dramatically inadequate. These frustration sessions invariably highlight the efforts of one discipline or group, leaving partner discipline participants in a state of limbo — asking "what does this mean to me," "how did we get here," "where are we going," "what have we learned." These sessions, however, have consistently provided a very valuable piece of information. They have shown that we have been pecking at this problem — each from the direction of his own discipline. The required and available capabilities have not as yet been integrated in a common effort which appropriately reflects interdisciplinary direction and contribution.

Though our report emphasizes physical concepts and engineering details which provide a logical technical base in support of conclusions and recommendations, there is an underlying theme which is keyed to the method of imp... ...tation. User involvement in a real and direct sense is the crux of this theme. There are many partners in this venture —

each represents some required discipline or capability. It is important to note, however, that the associated disciplinary objectives are not necessarily compatible in the short term. Consequently, the organization of the research program is as critical to its success as those who participate.

More meaningful results require a more meaningful and direct participation of representatives of the related disciplines in each phase of an experimental program -- starting with definition and planning and proceeding through instrument assembly and data accumulation — to the analysis and interpretation of the data. The User is, perhaps, the most critically important participant since he is best equipped to:

(1) Interpret the usefulness of results in terms of his immediate needs.

(2) Provide the correlation of observed microwave characteristics with those physical conditions most important to him.

It is evident that through an effective plan of joint participation, the product of each effort would reflect the criteria of "usefulness" imposed by the User. This does not imply that what might otherwise be accomplished without benefit of User participation would not be useful, but it does mean that one could interpret useful as "more immediately applicable" with a greater degree of confidence.

A frequently asked question is: "what are the User requirements?" It is interesting that this question persists when so many have discussed it with Users on so many occasions. The User has consistently given the answer to this question. What he would like is a useful system which is reliable and simple. By "system," he means a data-gathering mechanism which includes consideration of the vehicle, the sensor, dara storage, compression, presentation, and usage -- the entire cycle. He is as concerned with the complexity of the sensor as he is with the interface between the steps of data acquisition and storage. He is concerned with the present ability to quickly acquire large quantities of accurate data and what this means in terms of the requirement to handle the data and quickly present it in a useful manner.

In brief, the User views his requirement as an overall system – an integral part of his total function.

Though there are a number of User Agencies, the commonality of their system needs has become apparent through our several discussions. To be truly helpful to the User, we cannot expect to operate in the partial vacuum of individual disciplines as has sometimes been done. We must join with the User and understand his total system requirements–as well as his concern with the individual pieces of hardware that make up the total data-gathering and usage mechanism.

We are not going to set aside the dichotomy between contributor objectives and User requirements through seminars and team meetings alone. These tend to highlight after-the-fact results. Each discipline can fruitfully become involved with the User at the very outset of any Earth Resource related program effort. This rapport is as important to advanced research and technology efforts as it is to experimental measurements programs in which available equipments are used.

This report amply describes what it is felt from the viewpoint of our own discipline should be done to optimize the contribution of microwave radiometry to Earth Resource applications. Though a major effort is required in the development of advanced instrumentation techniques, the usefulness of the end product would benefit immeasurably through the early and continued participation of User expertise and advice. Representatives of several User Agencies, contacted during this study, shared an equal degree of enthusiam for an approach along these lines.

5.2 Research and Engineering Plan

The objectives of a recommended Research and Engineering Program are twofold:

(1) Develop the passive microwave instrument technology required to provide more effective methods for the accumation and interpretation of observational data obtained from airborne observing platforms.

(2) Apply the advanced techniques developed under Item (1)

to the low frequency region to establish the efficacy of these new techniques and accelerate the exploitation of the benefits to be derived from data obtained at these low frequencies.

Implementation of this program should be predicated on the identification of critical technological milestones and a common denominator approach to the achievement of these milestones. The investigation of the total system concept should proceed along the lines of a "building-block approach." This would concentrate attention in a logical investigative sequence on those areas which require advanced technique development. Verification of the performance achieved at each technological milestone would be obtained through carefully planned and executed supporting measurements.

The "building-block approach" has the following advantages:

(1) Minimizes development risks by identifying dependent relationships between the several advanced techniques required for the total system. The investigarion of each technique can be scheduled in an orderly sequence at the subsystem level. Verification of the desired performance could be obtained by configuring the subsystem in a useful measurement instrument form to allow verification of anticipated performance, as well as the accumulation of data that would benefit through User analysis.

(2) Provides adequate lead time to consider design approaches which will reduce instrument size and complexity and improve the reliability of each subsystem before its introduction in the follow-on building-block cycle.

(3) Provides an effective means for coupling the total program effort to User involvement through a sequence of measurements initiated early in the program and continued throughout the various phases of the program.

A research and engineering program along these lines should result in the development and evaluation of advanced techniques to provide a simultaneous dual polarization multiple beam imaging capability; and by simple mechanical rotation of the sensor head through 90°, a continuous series of parametric displays along the ground track of airborne observing platforms. Technical areas of concern, in order of priority, include:

(1) Simultaneous operation of N radiometers, where N is twice the number of look angles. This will provide the desired image in both polarizations.

(2) Antenna configurations, in particular, their integration with airborne observing platforms.

(3) Data recording and display subsystems for parametric and imagery modes.

(4) Definition of experimental measurements to verify anticipated performance.

(5) Selection of observing frequencies.

The logic of the "building-block approach" becomes most readily apparent when one considers certain common denominators in each of the areas listed above which are independent of the final form of the system configuration, but establish the requirements that must be accommodated by any configuration. Those factors which are common in each area are briefly summarized in the discussion which follows.

Simultaneous Operation of N Radiometers

The associated technology requirements are similar to those encountered in "line radiometry" (radiometric sensors developed in radio astronomy for the measurement of interstellar gas resonant line profile characteristics). In the decade of the '50's, line radiometers were predominately of the single receiver frequency scanning type. By the end of that decade, it became apparent that improvement in sensitivity dictated the need for simultaneous multiple channel techniques. These techniques are now fully developed and few, if any, frequency scanning radiometers are now in use. The logic supporting multi-channel operation for line profile resolution is identical to that which supports the value of multiple beam imagery, i.e., $\sqrt{N}$ improvement in sensitivity. The line radiometer obtains improvement in sensitivity through simultaneous multiple frequency observations, using N contiguous filters in the frequency domain. The imager obtains improvement in sensitivity through the use of N contiguous filters in the spatial domain (antenna beams). Each filter operates at the same frequency, since the information content for small bandwidths is, in this case, contained in the spatial rather than frequency domain.

Recognition of the common denominator aspects of line radiometry and multiple beam imagery is of considerable advantage since there are a variety of potential solutions to the "simultaneous operation of N radiometers" that can be applied directly from related engineering efforts in line radiometry during the past decade.

Antenna Design

The antenna problem area, as discussed in Section 4.0, is the structural interface between the antenna and the airborne platform. At the shortest wavelength in the low frequency region, the required antenna aperture diameter for a 6^{o} antenna beam is approximately 1.5 meters. At the longest wavelength, 300 MHz, the size requirement increases to 10 meters. It is clear that the common denominator, insofar as the antenna design is concerned, will be the mechanical interface with the airborne platform independent of the wavelength of operation. Helicopter or blimp observing platforms may be the most reasonable solution for evaluation of long wavelength systems.

Data Recording and Display

The technologies associated with data recording and displays have become well-developed in recent years. The variety of approaches and degrees of sophistication available suggests that this subsystem function will not require advanced development. The parametric and imagery display requirements for passive microwave sensors are common to several optical and infrared sensors. Compatibility of microwave radiometric system outputs with presently available data recording and display systems is a logical approach. This approach recognizes the commonality of this subsystem function with other sensors and capitalizes on available equipments. Investigations in this area, currently in process at Purdue University, as well as improvements in color imagery displays presently being developed for NASA by the Bendix Corporation, are good examples of present work in this area.

Supporting Measurements

Though the prime objective of supporting measurements would be to verify anticipated subsystem and system performance characteristics at each significant technological milestone, User involvement in the planning of these experiments and interpretation of the resultant data would provide an effective avenue for interdisciplinary interchange of concepts and requirements. To proceed with the development of advanced engineering concepts, in virtual isolation from those who will benefit from and establish the usefulness of these advancements, runs the serious risk of developing a sophisticated sensor system which may be optimum from the engineering standpoint, but of little immediate benefit or value to the User. An effective level of inter-action with potential Users throughout the program would assure that the product of the effort is of immediate value to the User, as well as optimum from an engineering standpoint.

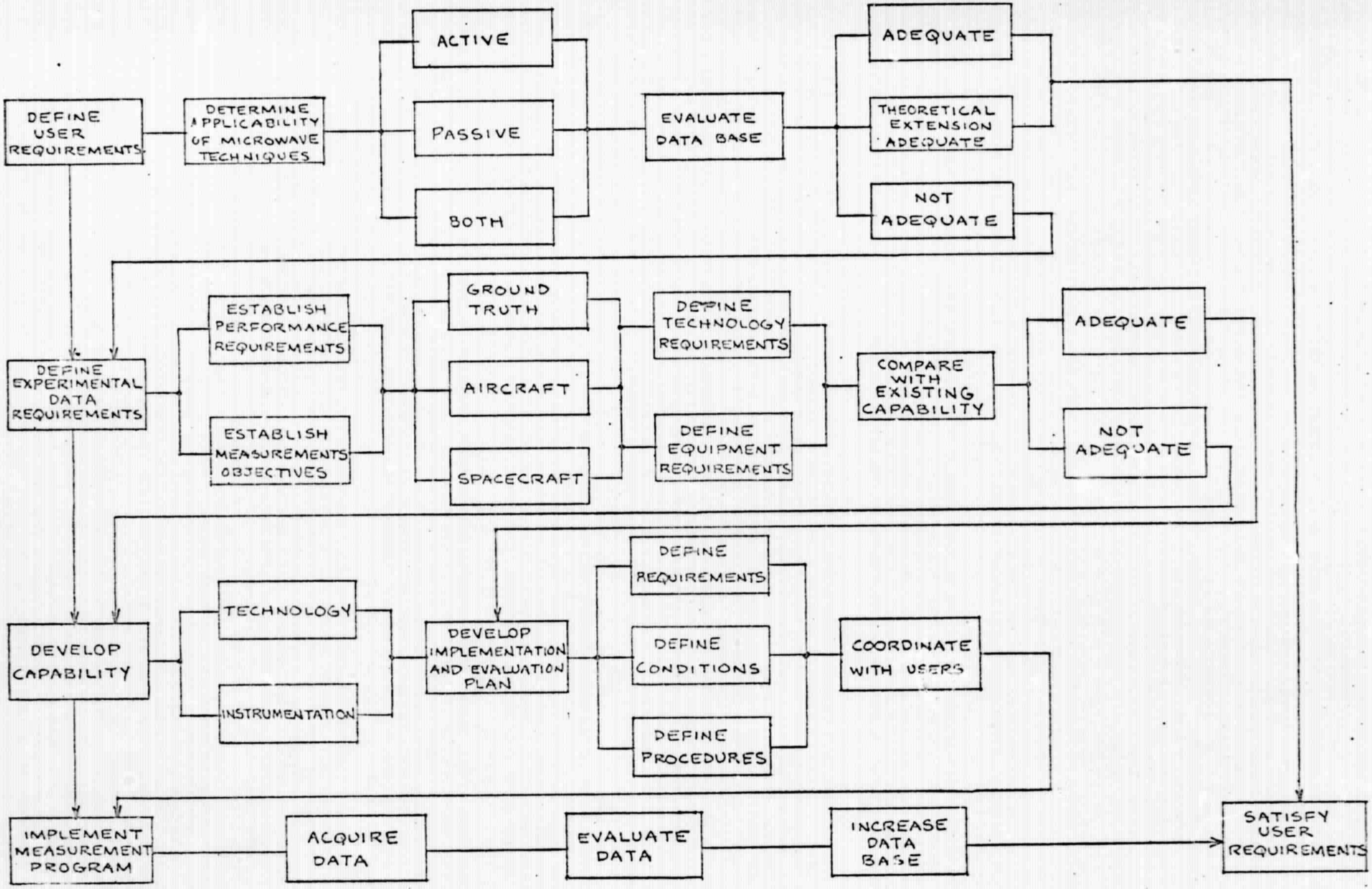
Selection of the "building-block approach" was influenced, in part, by the desire to assure an effective level of User involvement in all phases of a research and engineering program. For example, the selection of the sequence in which measurement instruments would be assembled and evaluated should reflect an organized plan to perform a series of measurements in which Users would participate in experiment planning and data interpretation.

Selection of Observing Frequencies

A prime concern in the low frequency region is radio frequency interference. The use of radio astronomy bands, as outlined in Section 4, is an optimum approach. To aid Users in the determination of the benefits to be gained from the low frequency region, a minimum of two wavelengths of operation are suggested: one at the upper end of the band, and the other at the low end. Simultaneous observations obtained at two widely separated wavelengths in the low frequency region, when compared with images obtained of the same terrain by presently instrumented high frequency systems, should provide meaningful data concerning the value of increased depth of penetration and insensitivity to surface roughness available through low frequency measurements.

A common denominator of prime concern in selection of the observing frequency is the fundamental relationship between the desired antenna beam angle and the wavelength of observation, as discussed in Section 4. This relationship leads immediately to consideration of structural interfaces between the antenna size and the mechanical capabilities of airborne platforms. Since the wavelength varies by a factor of 7:1 over the low frequency region, it is recommended that the initial measurement system configuration be at the shortest wavelength in the low frequency region, consistent with radio astronomy band allocations. This would require the smallest antenna and thereby allow concentration on instrument technique development (N radiometer problem) with a minimum of vehicle interface considerations.

The various steps involved in a building-block approach are shown in flow diagram form in Figure 5-1.



BUILDING BLOCK APPROACH TO
SENSOR APPLICATION DEVELOPMENT
FIGURE 5-1

APPENDIX A

DOCUMENT INDEX

(Unclassified)

APPENDIX A - DOCUMENT INDEX (Unclassified)

Documents listed in the Index have been grouped under five main headings:

(1) Earth Resources

(2) Agriculture and Forestry

(3) Geology and Hydrology

(4) Oceanography and Marine Technology

(5) Techniques and Exploratory Measurements

A number of the documents are drawn from the listings of the Scientific and Technical Aerospace Reports Center (N-numbered series), the Defense Documentation Center (AD-numbered series) and the American Institute of Aeronautics and Astronautics (A-numbered series). Pertinent papers from the Proceedings of the Fifth, Fourth, and Third Symposium on Remote Sensing of Environment (University of Michigan) are identified only by the notations of Fifth Symposium, Fourth Symposium, and Third Symposium, respectively. In the same way, papers from the Proceedings of the Conference on the Feasibility of Conducting Oceanographic Explorations from Aircraft, Manned Orbital and Lunar Laboratories are identified only by the notation, Woods Hole Document No. 65-10 (Oceanography from Space).

An alphabetical listing of authors is included on pages A-16 through A-19 for cross-reference purposes.

EARTH RESOURCES

Alexander, R.H., 1964, Geographic Research Potential of Earth-Satellites, Third Symposium.

Badgley, P.C., 1966, Current Status of NASA's Natural Resources Program, Fourth Symposium.

Badgley, P.C., and Vest, W.L., 1966, Unique Advantages of Orbital Remote Sensing for the Study of Natural Resources-Presentation at the Annual Meeting of the American Society of Photogrammetry, Washington, D.C.

Colwell, R.N., 1968, Remote Sensing of Natural Resources, Scientific-American, January Issue

Environmental Science Services Administration, 1968, Man's Geophysical Environment - Its Study from Space, U.S. Dept. of Commerce.

House Subcommittee on Space Science and Applications, 1968, Earth Resources Satellite System, Subcommittee Report.

Kondratyev, K. and Skuridin, G., 1968, Satellites Study Earth's Natural Resources, Moscow Pravda Article.

Leestma, R.A., 1966, Applications of Air and Spaceborne Sensor Imagery for the Study of Natural Resources, Fourth Symposium.

National Academy of Sciences, 1969, Useful Applications of Earth-Oriented Satellites - Report of the Central Review Committee.

National Academy of Sciences, 1969, Useful Applications of Earth-Oriented Satellites - Summaries of Panel Reports.

National Academy of Sciences, 1969, Useful Applications of Earth-Oriented Satellites, Meteorology, Panel Report.

National Academy of Sciences, 1969, Useful Applications of Earth-Oriented Satellites, Points-to-Point Communication, Panel Report.

National Academy of Sciences, 1969, Useful Applications of Earth-Oriented Satellites - Systems for Remote-Sensing Information and Distribution, Panel Report.

National Academy of Sciences, 1969, Useful Applications of Earth-Oriented Satellites - Geodesy-Cartography, Panel Report.

Newell, H.E., 1968, Current Program and Considerations of the Future for Earth Resources Survey, Fifth Symposium.

Simonett, D.S., 1966, Present and Future Needs of Remote Sensing in Geography, Fourth Symposium.

University of Michigan, 1968, Proceedings of the Fifth Symposium on Remote Sensing of Environment.

University of Michigan, 1966, Proceedings of the Fourth Symposium on Remote Sensing of Environment.

University of Michigan, 1964, Proceedings of the Third Symposium on Remote Sensing of Environment.

AGRICULTURE AND FORESTRY

Aldrich, R.C., 1968, Remote Sensing and the Forest Survey - Present Applications, Research, and a Look at the Future, Fifth Symposium.

Cooper, C.F., 1964, Potential Applications of Remote Sensing to Ecological Research, Third Symposium.

Gates, D.M., 1964, Characteristics of Soil and Vegetated Surfaces to Reflected and Emitted Radiation, Third Symposium.

Gensurowsky, W., 1968, Applications of Economic Analysis to Problems of Data Collection by Remote Sensing Techniques, Fifth Symposium.

Heller, R.C., 1968, Previsual Detection of Ponderosa Pine Trees Dying from Bark Beetle Attack, Fifth Symposium.

Holmes, R.A., and MacDonald, R.B., 1969, The Physical Basis of System Design for Remote Sensing in Agriculture, IEEE Proceedings, 57-4.

Myers, V.I. and others, 1966, Remote Sensing in Soil and Water Conservation Research, Fourth Symposium

National Academy of Sciences, 1969, Useful Applications of Earth-Oriented Satellites - Forestry-Agriculture-Geography, Panel Report.

Shay, J.R., 1966, Some Needs for Expanding Agricultural Remote Sensing Research, Fourth Symposium.

U. S. Department of Agriculture and others, 1967, A National Program of Research for Remote Sensing, Task Report.

Wiegand, C.L. and others, 1968, Detailed Plant and Soil Thermal Regime in Agronomy, Fifth Symposium.

Wilson, R.A., 1968, Fire Detection Feasibility Tests and System Development, Fifth Symposium

Wilson, R.C., 1966, Forestry Applications of Remote Sensing, Fourth Symposium.

GEOLOGY AND HYDROLOGY

Cain, S.A., 1966, Current and Future Needs for Remote Sensor Data in Ecology, Fourth Symposium.

Carr, D.D. and Blakeley, R.F., 1965, Temperature Variations at a Depth of 30 Centimeters in Clay Till, Fourth Symposium.

Fischer, W.A., 1966, Geologic Applications of Remote Sensors, Fourth Symposium.

Gerlach, A.C., 1968, Advances in Geographic and Thematic Mapping Applications of Remote Sensor Data, Fifth Symposium.

Meier, M.F., and Others, 1966, Multispectral Sensing Tests at South Cascade Glacier, Washington, Fourth Symposium.

National Academy of Sciences, 1969, Useful Applications of Earth-Oriented Satellites - Geology, Panel Report.

National Academy of Sciences, 1969, Useful Applications of Earth-Oriented Satellites - Hydrology, Panel Report.

Robinove, C.J., 1968, The Status of Remote Sensing in Hydrology, Fifth Symposium.

Robinove, C.J., 1966, Remote Sensor Applications in Hydrology, Fourth Symposium.

OCEANOGRAPHY AND MARINE TECHNOLOGY

Bruun, P., 1965, Possibilities for Use of Space and Other High Altitude Vehicles for Gathering of Coastal Engineering Data, Woods Hole Document 65-10.

Cameron, H.L., 1965, Radar and Ice Surveys, Woods Hole Document 65-10.

Clark, J. and Stone, R.B., 1965, Marine Biology and Remote Sensing Woods Hole Document 65-10.

Clarke, G.L., 1965, Transparency, Bioluminescence and Plankton. Woods Hole Document 65-10.

Cox, C. and Munk, W., 1954, Measurement of the Roughness of the Sea Surface from Photographs of the Sun's Glitter, J. Opt. Soc. Am., 44, No. 11.

Ewing, G.C., 1966, Current and Future Needs for Remotely Sensed Oceanography Data - A Speculation, Fourth Symposium.

Ewing, G.C., 1964, The Outlook for Oceanographic Observations from Satellites, Third Symposium.

Fairbridge, R.W., 1965, Coastal Processes, Woods Hole Document 65-10.

Galler, S.R., 1965, Possible Contributions of Manned and Unmanned Satellites Toward Advancing the Fields of Marine Biology and Biological Oceanography, Woods Hole Document 65-10.

Iselin, C.O., 1965, Oceanographic Forecasting, Woods Hole Document 65-10.

Laevastu, T., 1966, Application of Synoptic Oceanographic Analyses/Forecasts to Fisheries, Fleet Numerical Weather Facility Report.

National Academy of Sciences, 1969, Useful Applications of Earth-Oriented Satellites - Oceanography, Panel Report.

Noble, V.E. and others, 1969, Some Aspects of Remote Sensing as Applied to Oceanography, IEEE Proceedings 57-4.

Phleger, F.B., 1965, Study of River Effluents from Space Vehicles, Woods Hole Document 65-10.

Pruitt, E.L., 1965, Use of Orbiting Research Laboratories for Experiments in Coastal Geology, Woods Hole Document 65-10.

Redfield, A.C., 1965, Estuaries, Woods Hole Document 65-10.

Salas, G.P., and Castanares, A.A., 1965, Status of Marine Geology Studies in Mexico, Woods Hole Document 65-10.

Saur, J.F.T., 1965, Oceanographic Observations from Manned Satellites for Fishery Research and Commercial Fishery Applications, Woods Hole Document 65-10.

Schuler, Jr., J.J., 1965, Relation of Thermocline Depth to Surface Temperature in the Atlantic, Woods Hole Document 65-10.

Shepard, F.P. 1965, Effect of Submarine Valleys on Water Masses and Currents, Woods Hole Document 65-10.

Squire, Jr., J.L., 1965, Airborne Oceanographic Programs of the Tiburon Marine Laboratory and Some Observations on Future Development and Uses of This Technique, Woods Hole Document 65-10.

Tully, J.P., 1965, The Possible Use of Satellite Data in Estimating the Depth of the Thermocline, Woods Hole Document 65-10.

Wolff, P.M., 1965, Operational Analysis and Forecasting of Ocean Temperatures Structure, Woods Hole Document 65-10.

Wolff, P.M., 1965, Future Use of Ships, Buoys, Airplanes and Satellites in Obtaining Oceanographic Observations for Environmental Prediction Systems, Woods Hole Document 65-10.

Woods Hole Oceanographic Institution, 1965, Oceanography from Space, Woods Hole Document 65-10.

Zaitzeff, J.B. and Sherman, J.W., 1966, Oceanographic Applications of Remote Sensing, Fifth Symposium.

TECHNIQUES AND EXPLORATORY MEASUREMENTS

Arams, F. and others, 1960, Design and Construction of Radiometric Mapping Set, AD 287118.

Arnold, J.E. and others, 1967, Ground Truth Requirements for Remote Sensing of Oceanographic Features, AD 663458.

Barber, N.F., 1962, Detecting Sea Waves by Their Diffraction of a Radio Wave, Woods Hole Document 62-39.

Barrett, A.H. and others, 1967, Radiometric Detection of Atmospheric Ozone, M.I.T. Research Lab. of Electronics, QPR 86.

Barrett, A.H., 1963, Microwave Spectral Lines as Probes of Planetary Atmospheres, Mem. Soc. Sci. Liege, Vol. 8.

Barrett, A.H. and Chung, V.K., 1962, A Method for the Determination of High-Altitude Water - Vapor Abundance from Ground-based Microwave Observations, J. Geophysical Research, Vol. 67.

Bauerle, D.G. and Richer, K.A., 1964, Near Earth Millimeter Wave Radiometer Measurements, Ballistic Research Laboratories Document 1267.

Baur, K., 1964, Phase Front Distortion Due to Soil Irregularities, AD 803711.

Bell Telephone Laboratories, 1956, Microwave Research, AD 101745.

Blacksmith, P. and others, 1957, A Method of Reducing Far Out Sidelobes, AD 133707.

Blinn, J. and others, 1968, Airborne Multi-Frequency Microwave Radiometric Survey of An Exposed Volcanic Province, NASA Tech Memo 33-405.

Block, M.J., 1964, Emissivity of Granular Surfaces at Resonance Frequencies, Third Symposium.

Bruno, D.J., 1963, Millimeter Radiometer Measurement Program, AD 421501.

Budd, W.E. and Fawcett, R.G., 1962, Correlation Techniques for Microwave Radiometric Sensors, AD 284044.

Capurro, L.R.A., 1969, Oceanography Using Remote Sensors, AD 682939.

Casey, W.L., 1968, The Importance of Elemental Registration and Calibration in Orbital Earth Resources Multi-Spectral Imaging, A68-1075.

Catoe, C.W. and others, 1967, Preliminary Results from Aircraft Flight Tests of an Electrically Scanning Microwave Radiometer, NASA X622-67-352.

Chalfin, G.T. and Rickets, W.B., 1966, 3.2 Millimeter Thermal Imaging Experiments, Fourth Symposium.

Chen, S.N.C., 1960, Apparent Temperatures of Smooth and Rough Terrain, Ohio State University, Antenna Lab. 898-8.

Collins Radio Company, 1961, Passive Microwave Observation of Terrain Features, Collins CRR-248.

Colwell, R.N., 1963, Platforms for Testing Multi-Sensor Equipment, Second Symposium.

Conway, W. and Yarbrough, L.A., 1966, Characteristics and Uses of an L-Band Radiometer, Fourth Symposium.

Conway, W.H. and Sakamoto, R.T., 1964, Microwave Radiometer Measurements Program, Third Symposium.

Cumming, W.A., 1952, The Dielectric Properties of Ice and Snow at 3.2 Centimeters, J. Applied Physics, 23-7.

Cummings, C.A. and Hull, J.W., 1966, Microwave Radiometric Meteorological Observations, Fourth Symposium.

Dereny, E.E., 1966, Geometrical Considerations For Mapping from Scan Imagery, Fourth Symposium.

Edgerton, A.T., 1968, Engineering Applications of Microwave Radiometry, Fifth, Symposium.

Edgerton, A.T., 1968, Passive Microwave Measurements of Snow, Ice, and Soil, AD 674927.

Eppler, W.G. and Merrill, R.D., 1969, Relating Remote Sensor Signals to Ground - Truth Information, IEEE Proceedings, 57-4.

Ewen, H.I., 1965, State of the Art of Microwave and Millimeter Wave Radiometric Sensors, International Symposium of Electromagnetic Sensing of the Earth from Satellites.

Ewen, H.I. and others, 1968, Microwave Radiometric Capabilities and Techniques, Fifth Symposium.

Falco, C.U. and Oister, G., 1967, Microwave Radiometer Design and Development, N68-16707.

Fu, K.S. and others, 1969, Information Processing of Remotely Sensed Agricultural Data, IEEE Proceedings, 57-4.

Fujimoto, K., 1962, On the Correlation Radiometer Technique, Ohio State University, Antenna Lab. 1093-6.

Gaut, N.E. and others, 1968, A General Analysis of Natural Environmental Effects on Electromagnetic Radiation Utilized for Communications, AD 667193.

George, N., 1959, Spatial Distribution of Thermal Radiation at Microwave Frequencies, AD217179.

Gilmore, H. F. and others, 1959, Atmospheric Absorption Effects of Radiometer Response, AD305475.

Greaves, J. R., 1966, Sea Surface Temperature Determination from Tiros Satellite Data, Fourth Symposium.

Grossman, R. L. and Marlatt, W. E., 1966, A Method of Showing What a Radiometer "Sees" During an Aircraft Survey, Fourth Symposium.

Gunn, K. L. S. and East, T. W. R., 1954, The Microwave Properties of Precipitation Particles, J. Royal Meteorological Soc. 80-346.

Gurvich, A. S. and Yegorov, S. T., 1966, Determination of Sea Surface Temperature from its Thermal Radio Emission, N66-28422.

Haralick, R. M. and Kelly, G.L., 1969, Pattern Recognition with Measurement Space and Spatial Clustering for Multiple Images, IEEE Proceedings, 57-4.

Hardman, W. E., 1959, A Sensitive Detection System for Electromagnetic Radiation with a Wave-Length of 4 Millimeters, AD229714.

Hodgin, D. M., 1963, The Characteristics of Microwave Radiometry in Remote Sensing of Environment, Second Symposium.

Holl, H. B., 1963, The Reflection of Electromagnetic Radiation, AD422882.

Hooper, O. J. and Battles, J. W., 1963, Some Calculations of Target Temperatures in Microwave Radiometry, AD402618.

Hoover, M. C. and other, 1965, Microwave Radiometric Contrasts: Measurement of Various Materials Against a Terrain Background, AD455551.

Hyatt, H. A., 1965, The Airborne Detection of Microwave Emission from the Earth's Atmosphere, International Symposium on Electromagnetic Sensing of the Earth from Satellite.

Janza, F. J., 1968, A Comparison of the Microwave Scatterometer and Radiometer for Sea-State Measurements, Annual Meeting of the American Geophysical Union.

Johnson, H. A., 1967, Detection, Sensitivity and Related Statistics of Microwave Radiometry, NOL report 735.

Kennedy, J., and Sakamoto, R.T., 1966, Passive Microwave Determinations of Snow Wetness Factors, Fourth Symposium.

Kreiss, W.T., Meteorological Observations with Passive Microwave Systems, Boeing No. D1-82-0692.

Legault, R. R. and Polcyn, F. C., 1964, Investigation of Multi-Spectral Image Interpretation, Third Symposium.

Limperis, T., 1964, Target and Background Signature Study, Third Symposium.

Lundien, J. R., 1966, Terrain Analysis by Electromagnetic Means, AD802104.

Mardon, A., 1964, Application of Microwave Radiometers to Oceanographic Measurements, Third Symposium.

McGillem, C. D. and Seling T. V., 1963, Influence of System Parameters on Airborne Microwave Radiometer Design, IEEE Transactions, MIL-7.

Molineux, C. E., 1964, Aerial Reconnaissance of Surface Features with the Multiband Spectral System, Third Symposium.

Moore, R. P. and others, 1964, Microwave Radiometric Contrasts of Metal Targets Against a Terrain Background, AD328578.

National Academy of Sciences, 1969, Useful Applications of Earth-Oriented Satellites-Sensors and Data Systems, Panel Report.

Nikodem, H. F., 1965, Effects of Soil Layering on the Use of VHF Radio Waves for Remote Terrain Analysis, Fourth Symposium.

Nordberg, W. and others, 1968, Microwave Observations of Sea State from Aircraft, N69-11537.

North American Aviation, 1965, Microwave Radiometric Data Measurement Program, North American 65H-176

Northrop Corporation, 1964, Radiometric Data Gathering Program, AD437134.

Ory, T. R., 1964, Line - Scanning Reconnaissance Systems in Land Utilization and Terrain Studies, Third Symposium.

Packard, R. F., 1964, Submillimeter Radiometer for the Detection and Acquisition of Ground Targets, AD464838.

Paris, J. F., 1969, Microwave Radiometry and Its Applications to Marine Meteorology and Oceanography, AD687127.

Pascalar, H. G. and Sakamoto, R. T., 1964, Microwave Radiometric Measurements of Ice & Water, Third Symposium.

Peake, W. H., 1959, The Interaction of Electromagnetic Waves and Some Natural Surfaces, Ohio State University Antenna Lab 898-2.

Peake, W. H., 1959, Apparent Temperature of Non-Uniform Surfaces, Ohio State University, Antenna Lab 898-3

Peake, W. H., 1961, The Apparent Temperature of Isolated Objects, Ohio State University, Antenna Lab 898-15.

Peake, W. H. and others, 1966, The Mutual Interpretation of Active and Passive Microwave Sensor Outputs, Fourth Symposium.

Porter, R.A. and Florance, E.T., 1969, Feasibility Study of Microwave Radiometric Remote Sensing, NAS12-629.

Rand Corporation, 1963, The Application of Passive Microwave Technology to Satellite Meterorology, Rand RM-3401-NASA.

Riegler, R.L., 1966, Microwave Radiometric Temperatures of Terrain, Ohio State University, Antenna Lab 1903-2.

Rinker, J.R. and others, 1966, Radio Ice-Sounding Techniques, Fourth Symposium.

Roberts, J.B., 1963, Microwave Temperature Mapping with an Airborne Antenna, AD424765.

Roberts, J.B., 1963, Effect of Antenna Beam Width in the Microwave Region, AD423843.

Roeder, R.S., 1967, Airborne Measurements with the AN/AAR-33 Radiometric Search Set.

Singer, S.F. and Williams, G.F., 1968, Microwave Detection of Precipitation over the Surface of the Ocean, J. Geoph. Res., 73, No. 10.

Sirounian, V., 1968, Effect of Temperature, Angle of Observation, Salinity, and Thin Ice on the Microwave Emission of Water, J. Geoph. Res., 73, No. 14.

Staelin, D.H., 1969, Passive Remote Sensing At Microwave Wavelengths, IEEE Proceedings 57-4.

Stogryn, A., 1967, The Apparent Temperature of the Sea at Microwave Frequencies, IEEE Transactions, AP-15.

Straiton, A.W. and others, 1958, Apparent Temperatures of Some Terrestrial Materials and the Sun at 4.3 Millimeter Wavelength, J. Applied Physics, 29.

Strom, L.D., 1957, The Theoretical Sensitivity of the Dicke Radiometer, AD156707.

Tobin, M., 1967, Support Data for Convair 990 Meteorological Flight, NASA X-622-67-450.

Tolbert, C. W. and Coats, G. T., 1963, Lunar Radiation at 3.2 Millimeters and a Lunar Model, AD417910.

University of Texas, 1952, Preliminary Study of the Reflection of Millimeter Radio Waves from Fairly Smooth Ground, University Texas report 60.

Vecchio, E., 1967, Emission from the Rough Sea, North American T7-2262/060.

Vivian, W. E., 1957, Capabilities and Limitations of a Radiometer System, AD134675.

Von Fragstein, C., 1955, Optik, 12, 60.

Weeks, W., 1967, Understanding the Variations of the Physical Properties of Sea Ice, AD657213.

Weger, E., 1965, The Radiative Properties of Some Terrestrial and Man-Made Materials at Microwave Frequencies, Raytheon FR-65-39.

Widger, Jr., W. K., 1966, Orbits, Altitudes, Viewing Geometry, Coverage, and Resolution Pertinent to Satellite Observations of the Earth and Its Atmosphere, Fourth Symposium.

Williams, G.F., 1969, Microwave Radiometry of the Ocean, and the Possibility of Marine Wind Velocity Determination from Satellite Observations (to be published).

Wortendyke, D., 1961, A Memorandum on an X-Band Radiometer Study Ohio State University, Antenna Lab 1041-3.

Alphabetical List

	Earth Resources	Agriculture and Forestry	Geology and Hydrology	Oceanography and Marine Technology	Techniques and Exploratory Measurements
Aldrich, R.C.		X			
Alexander, R.H.	X				
Arams, F.					X
Arnold, J.E.					X
Badgley, P.C.	X				
Barber, N.F.					X
Barrett, A.H.					X
Battles, J.W.					X
Bauerle, D.G.					X
Baur, K.					X
Bell Tel. Labs					X
Blacksmith, P.					X
Blakeley, R.F.			X		
Blinn, J.					X
Block, M.J.					X
Bruno, D.J.					X
Bruun, P.				X	
Budd, W.E.					X
Cain, S.A.			X		
Cameron, H.L.				X	
Capurro, L.R.A.					X
Carr, D.D.			X		
Casey, W.L.					X
Castanares, A.A.				X	
Catoe, C.W.					X
Chalfin, G.T.					X
Chen, S.N.C.					X
Chung, V.K.					X
Clark, J.				X	
Clarke, G.L.				X	
Coats, G.T.					X
Collins Radio Company					X
Colwell, R.N.	X				X
Conway, W.					X
Cooper, C.F.		X			
Cumming, W.A.					X
Cummings, C.A.					X
Dereny, E.E.					X
East, T.W.R.					X
Edgerton, A.T.					X

Alphabetical List

	Earth Resources	Agriculture and Forestry	Geology and Hydrology	Oceanography and Marine Technology	Techniques and Exploratory Measurements
ESSA	X				
Eppler, W.G.					X
Ewen, H.I.					X
Ewing, G.C.				X	
Fairbridge, R.W.				X	
Falco, C.U.					X
Fawcett, R.G.					X
Fischer, W.A.			X		
Florance, E.T.					X
Fu, K.S.					X
Fujimoto, K.					X
Galler, S.R.				X	
Gates, D.M.		X			
Gaut, N.E.					X
Gensurowsky, W.		X			
George, N.					X
Gerlach, A.C.			X		
Gilmore, H.F.					X
Greaves, J.R.					X
Grossman, R.L.					X
Gunn, K.L.S.					X
Gurvich, A.S.					X
Haralick, R.M.					X
Hardman, W.E.					X
Heller, R.C.		X			
Hodgin, D.M.					X
Holl, H.B.					X
Holmes, R.A.		X			
Hooper, O.J.					X
Hoover, M.C.					X
House Subcommittee	X				
Hull, J.W.					X
Hyatt, H.A.					X
Iselin, C.O.				X	
Janza, F.J.					X
Johnson, H.A.					X
Kelly, G.L.					X
Kennedy, J.					X
Kondratyev, K.	X				
Kreiss, W.T.					X

Alphabetical List

	Earth Resources	Agriculture and Forestry	Geology and Hydrology	Oceanography and Marine Technology	Techniques and Exploratory Measurements
Laevastu, T.				X	
Leestma, R.A.	X				
Legault, R.R.					X
Limperis, T.					X
Lundien, J.R.					X
MacDonald, R.B.		X			
Mardon, A.					X
Marlatt, W.E.					X
McGillem, C.D.					X
Meier, M.F.			X		
Merrill, R.D.					X
Molineux, C.E.					
Moore, R.P.					X
Myers, V.I.		X			
Natl. Acad. Sciences	X	X	X	X	X
Newell, H.E.	X				
Nikodem, H.F.					X
Noble, V.E.				X	
Nordberg, W.					X
North American					X
Northrop Corp.					X
Oister, G.					X
Ory, T.R.					X
Packard, R.F.					X
Paris, J.F.					X
Pascalar, H.G.					X
Peake, W.H.					X
Phleger, F.B.				X	
Polcyn, F.C.					X
Porter, R.A.					X
Pruitt, E.L.				X	
Rand Corp.					X
Redfield, A.C.				X	
Riegler, R.L.					X
Richer, K.A.					X
Rickets, W.B.					X
Rinker, J.R.					X
Robinove, C.J.			X		
Roberts, J.B.					X
Roeder, R.S.					X

Alphabetical List

	Earth Resources	Agriculture and Forestry	Geology and Hydrology	Oceanography and Marine Technology	Techniques and Exploratory Measurements
Sakamoto, R.T.					X
Salas, G.P.				X	
Saur, J.F.T.				X	
Schuler, Jr., J.J.				X	
Seling, T.V.					X
Shay, J.R.		X			
Shepard, F.P.				X	
Sherman, J.W.				X	
Simonett, D.S.	X				
Singer, S.F.					X
Sirounian, V.A.					X
Skuridin, G.	X				
Squire, Jr., J.L.				X	
Staelin, D.H.					X
Stogryn, A.					X
Stone, R.B.				X	
Straiton, A.W.					X
Strom, L.D.					X
Tobin, M.					X
Tolbert, C.W.					X
Tully, J.P.				X	
USDA		X			
Univ. of Michigan	X				
Univ. of Texas					X
Vecchio, E.					X
Vest, W.L.	X				
Vivian, W.E.					X
Weeks, W.					X
Weger, E.					X
Widger, Jr., W.K.					X
Wiegand, C.L.		X			
Williams, G.F.					X
Wilson, R.A.		X			
Wilson, R.C.		X			
Wolff, P.M.				X	
WHOI				X	
Wortendyke, D.					X
Yarbrough, L.A.					X
Yegorov, S.T.					X
Zaitzeff, J.B.				X	

APPENDIX B

PHYSICS OF MICROWAVE REMOTE SENSING

APPENDIX B

PHYSICS OF MICROWAVE REMOTE SENSING

By: D.H. Staelin

Antenna Temperature

The microwave properties of the terrestrial surface and atmosphere are quite varied, and by sensing these variations radiometrically, the nature of the surface and atmosphere may be studied. More specifically, all natural substances radiate and absorb thermal radiation at all wavelengths, including radio wavelengths, and the power radiated depends only upon the temperature, T, of the substance and the coupling coefficient, $\epsilon(\theta, \phi)$, between the substance and the radiation field in a given direction of interest. This radiation field may be coupled to an antenna and thence to a radiometer which measures the field intensity as a function of wavelength, viewing angle, polarization, or other variables of interest.

A radiometer is basically a power-measuring device, and for wavelengths longer than approximately one millimeter, the power received by a radiometer perfectly coupled to a black-body of temperature, T (°K), is approximately:

$$P = kTB \text{ watts,} \tag{1}$$

where k is Boltzmann's constant (1.38×10^{-23} J°K) and B is the receiver bandwidth (Hz). This approximation is valid if $h\nu << kT$, where h is Planck's constant (6.625×10^{-34} J sec) and ν is the signal frequency (Hz). Since there is a direct relationship between physical temperature and received power, most radiometers are calibrated in terms of temperature instead of power. Antenna temperature, T_A, is the temperature a black body at the antenna terminals must have to produce a signal of the observed power P,

$$T_A = P/kB \tag{2}$$

Brightness Temperature

The antenna temperature, T_A, is related in turn to the angular distribution of power incident upon the antenna, which may be characterized by the brightness temperature, $T_{B_1}(\nu, \theta, \phi)$ and $T_{B_2}(\nu, \theta, \phi)$, where ν is the frequency (Hz), and θ, ϕ are vector coordinates. T_{B_1} and T_{B_2} correspond to the brightness temperature in two orthogonal polarizations, of which any particular antenna port may intercept only one. If T_{B_1} corresponds to vertical polarization (the electric vector $\vec{E}$ is vertical), and the antenna is vertically polarized, then

$$T_A = \frac{1}{4\pi} \int_{4\pi} T_{B_1}(\nu, \theta, \phi)\, G_1(\nu, \theta, \phi)\, d\Omega \tag{3}$$

where $G_1(\nu, \theta, \phi)$ is the vertical polarization antenna gain function. The antenna gain function may be defined such that the received power P is:

$$P = \frac{c^2}{8\pi k \nu^2} \int_{\nu_1}^{\nu_2} \int_{4\pi} I_1(\nu, \theta, \phi)\, G_1(\nu, \theta, \phi)\, d\Omega \tag{4}$$

where the specific intensity of the radiation field is $I_1(\nu, \theta, \phi)$ watts $m^{-2}\ Hz^{-1}\ ster^{-1}$, and is proportional to the brightness temperature, T_{B_1}. In remote sensing it is always more convenient to talk in terms of temperatures rather than powers, so P and I will not be used further here. A good summary of these relations is contained in the work by Kraus[1].

The Atmosphere

The brightness temperature, T_B, viewed by the antenna is affected by the atmosphere intervening between the surface and the radiometer. If $T_{o_i}(\nu)$ is the brightness temperature which would be viewed by a radiometer looking directly at the surface at ground level with polarization i, then the brightness temperature in a particular direction is:

$$T_{B_i}(\nu) = T_{o_i}(\nu)\, e^{-\tau(\nu)} + \int_0^{z_{MAX}} T(z)\, e^{-\int_0^z \alpha(\nu, z)\, dz}\, \alpha(\nu, z)\, dz \tag{5}$$

where T (z) and α (ν , z) are, respectively, the temperature and absorption coefficient of the atmosphere along the ray path z. The equation states that the total radiation field is the sum of the attenuated surface radiation and the radiation emitted by each element of the atmosphere attenuated by the intervening atmosphere. The equation is valid in practice for most cases of interest, except perhaps heavy rain or snow at wavelengths shorter than 3 cm. In these cases, scattering is important. Methods for handling scattering are discussed by Chandrasekhar[2], Staelin[3], and others.

The principal atmospheric constituents which absorb microwave radiation are O_2, H_2O, clouds, and precipitation. The microwave properties of these materials and methods for studying the atmosphere using microwave radiometry have been reviewed by Staelin[4]. In cases where the surface properties are of greatest interest it is necessary only to approximate atmospheric effects to some desired degree of accuracy, and a complete characterization of the atmosphere is often not necessary. In this case, Equation (5) may become:

$$T_{B_i}(\nu) = T_{o_i}(\nu)\, e^{-\tau(\nu)} + \bar{T}_{atm}\left(1 - e^{-\tau(\nu)}\right) \tag{6}$$

where $\bar{T}_{atm}$ is the average temperature of the absorbing portion of the atmosphere and $\tau(\nu)$ is the atmospheric optical depth (nepers) between the observer and the surface. Figure BI shows the atmospheric opacity at zenith for a typical atmosphere.

The Terrestrial Surface

The microwave radiation from the surface T_{o_i} (ν) is determined primarily by the kinetic temperature of the surface, T_s , and the composition and roughness of the surface. In addition, there is a component of T_{o_i} contributed by the reflected sky radiation. Over ocean or at wavelengths less than approximately two centimeters, this component is non-negligable, and can be determined using the usual equation of radiative transfer. If the surface is smooth, then the surface brightness temperature T_{o_i} is given by:

$$T_{o_i}(\nu, \theta, \phi) = \bar{T}_{gnd}\, \epsilon_i(\nu, \theta, \phi) + T_{SKY}\left(1 - \epsilon_i(\nu, \theta, \phi)\right) \tag{7}$$

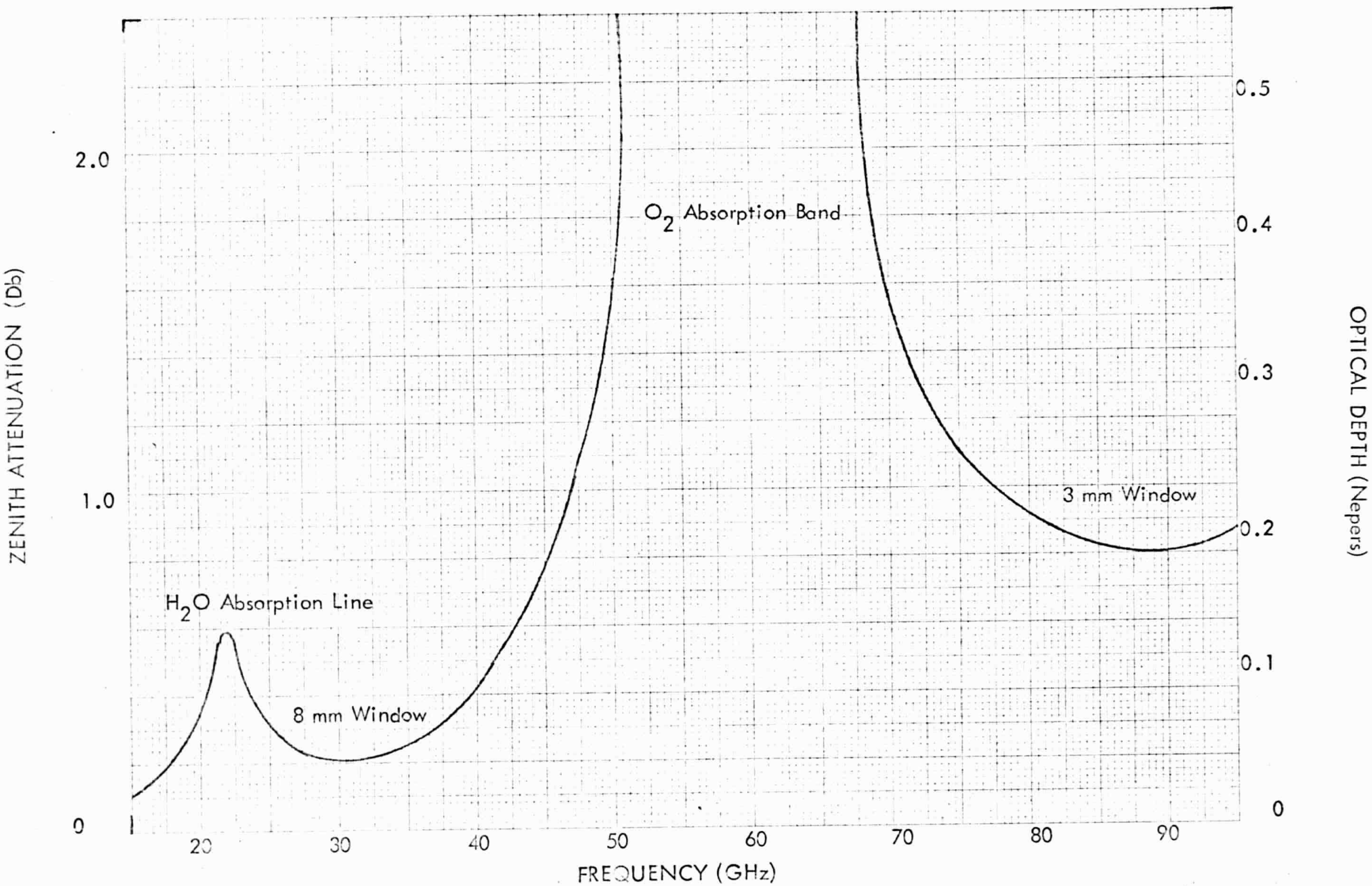


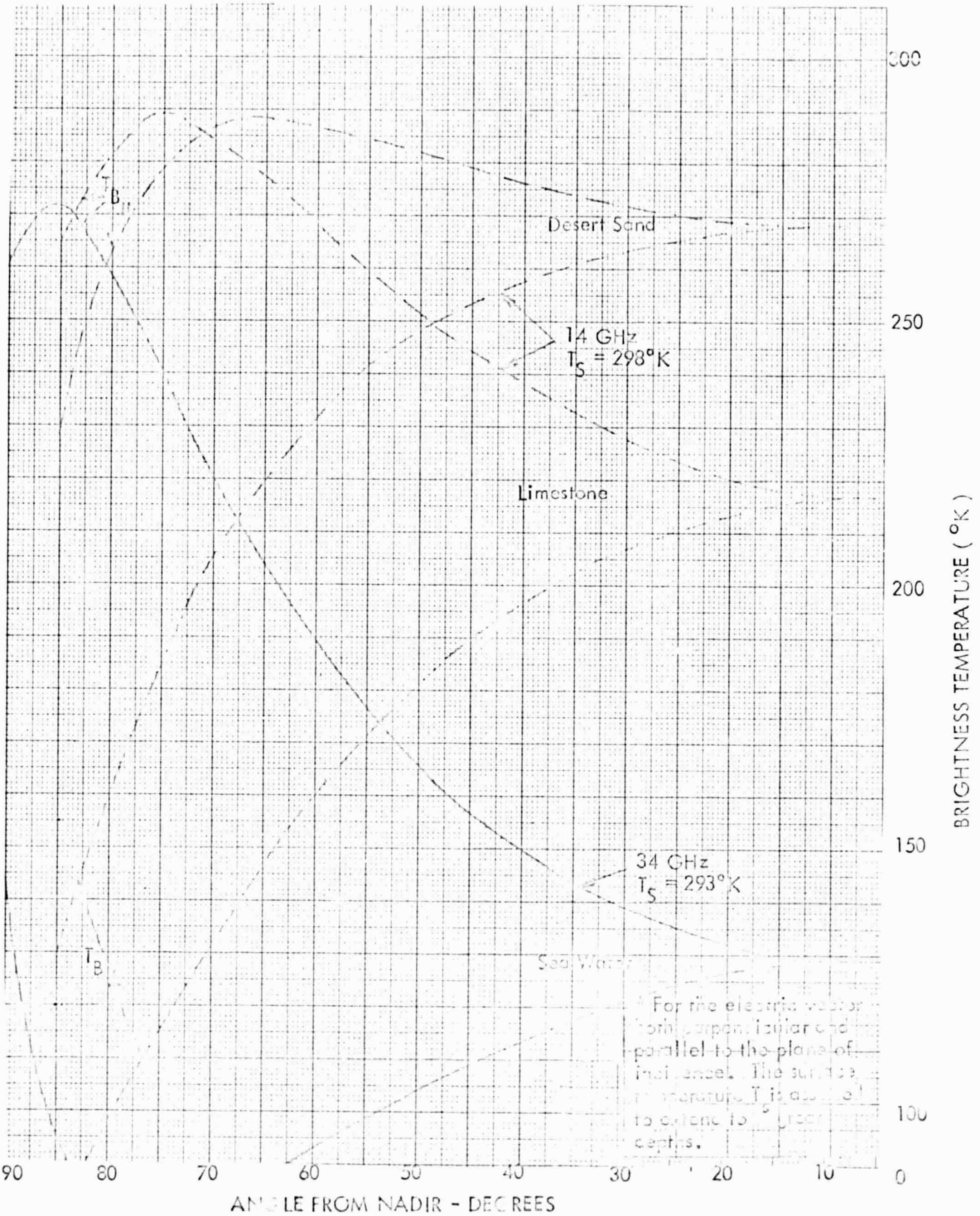
FIGURE B1 - APPROXIMATE ZENITH OPACITY OF THE TERRESTRIAL ATMOSPHERE where $\overline{T}_{gnd}$ is the average temperature of the surface layer which is effectively radiating. The thickness of this layer may vary from less than one-tenth wavelength, in the case of water, to more than ten wavelengths, for dry quartz sand. Equation (5) can be used not only for propagation within gases but also within solids or liquids, provided the material is sufficiently uniform and homogeneous so that scattering can be neglected, and provided the decay length of the electromagnetic fields, i.e. the effective thickness of the radiating surface layer, is much longer than one wavelength.

The emissivity, $\epsilon_i(\nu_i, \theta, \phi)$, is related to the permittivity, ξ, and permeability, μ, of the medium. In most cases, the permeability is approximately that of free space, and so that assumption is made in Equation (8). If the surface is smooth and homogeneous, then the emissivity for $\vec{E}$ perpendicular to the plane of incidence is[5]:

$$\epsilon_{\perp} = 1 - \left[\frac{\cos\theta - (K_e - \sin^2\theta)^{1/2}}{\cos\theta + (K_e - \sin^2\theta)^{1/2}}\right]^2 \tag{8}$$

$$\epsilon_{\parallel} = 1 - \left[\frac{(K_e - \sin^2\theta)^{1/2} - K_e\cos\theta}{(K_e - \sin^2\theta)^{1/2} + K_e\cos\theta}\right]^2 \tag{9}$$

where $\epsilon_{\perp}$ is the emissivity for radiation with the electric vector $\vec{E}$ perpendicular to the plane of incidence, and $\epsilon_{\parallel}$ is the emissivity for the orthogonal polarization. K_e is defined as ξ/ξ_o, ξ_o is the permittivity of free space, and θ is the angle between the ray and the surface normal. The emissivity curves for quartz sand, limestone, and sea water at two polarizations are shown in Figure B2, as computed by Marandino[6]. Given a homogeneous substance with a smooth surface, then measurement of its emissivity as function of viewing angle and polarization permits the measurement of both μ and ξ. In practice, most terrestrial surface materials are too inhomogeneous and have surfaces too rough to permit more than rather crude measurements of ϵ. One effect of surface roughness on a scale longer than a wavelength is to produce an effective emissivity which



BRIGHTNESS TEMPERATURE OF SMOOTH SURFACES*

FIGURE B 2

is approximately the convolution of the slope probability distribution $p(\Theta, \phi)$ and the emissivity function $\epsilon(\nu, \Theta, \phi)$ [7, 8]. A second effect is to increase the emissivity in all directions because surface structure smaller than a wavelength usually permits a smoother electromagnetic transition between the material and space. For example, heavy vegetation possesses a high emissivity which is nearly unity for all but grazing angles of incidence.

Surface brightness temperature is dependent not only upon surface roughness and the material properties, but also upon the observing frequency. For any given material, the penetration depth is approximately proportional to wavelength, depending upon the loss tangent of the material. If the material is isothermal, then the penetration depth is less important, but if there is a temperature gradient, as there is in sun-exposed rocks, then the wavelength dependence of the day-night brightness temperature cycle may provide clues to the ratio of the electrical penetration depth and the thermal wave penetration depth, i.e. the relationship between the thermal and electrical conductivity.

By observing the terrestrial surface one might hope to:

1) Estimate the emissivity and hence the effective dielectric constant.
2) Estimate the relationship between the thermal and electrical conductivity by observations over a day.
3) Estimate the character of surface roughness by measuring the polarization and angle dependence of the emissivity.
4) Estimate the drainage characteristics of surfaces by observations before and after precipitation.
5) Estimate the fullness, height, and moisture content of snow cover.
6) Detect the presence and character of ice cover over bodies of water, etc.

The accuracy with which such estimates can be made has not yet been determined because of the extensive measurement program which would be required.

The ocean is a separate problem because its high reflectivity makes the atmospheric effects much more important, and because the simplicity of the medium compared to that of land makes the ocean more amenable to quantitative analysis. There are three major categories of effects to be considered. First are the smooth surface effects which are dominated by the temperature, wavelength, and viewing angle dependence of emissivity, and by the reflected atmospheric radiation. The temperature dependence of the emissivity is such as to make the ocean brightness temperature nearly independent of temperature at some wavelengths, and of increased sensitivity at others. These wavelengths of minimum and maximum sensitivity are a function of water temperature. The second major effect is that of an undulating surface with facets larger than a wavelength. The statistical distribution of surface slopes should be measureable because the effective emissivity is approximately the convolution of the angular distribution of surface slopes, and the angular dependence of emissivity[7, 8]. Reflection of atmospheric radiation becomes important here too. The third effect is that of foam, spray, etc. This effect is important for winds above approximately 10 knots, and can be distinguished from the other two effects by its relative independence of viewing angle. The increase in T_B is approximately 0.7°K per knot wind speed, for vertical incidence.

Inference of Material Parameters from Measurements of Antenna Temperature

The inference of material parameters may be considered as a two-step procedure. First, the brightness temperatures in directions of interest must be inferred from the measured antenna temperatures, which represent weighted integrals of brightness temperature over 4π steradians (see Equation 3). Then, the material parameters must be inferred from the inferred brightness temperature as a function of frequency, viewing angle, polarization, etc.

The first step of inferring brightness temperatures from antenna temperatures is the easier of the two. It is more tractable mathematically because the relationship between brightness temperature and antenna temperature is a linear one. In particular, it is easy to show that it is impossible to reconstruct exactly the true brightness temperature distribution Instead one may obtain at best the true brightness temperature distribution convolved with a gaussian-like function of width somewhat less than the nominal antenna beamwidth. Such a procedure is sufficient to reduce the effects of antenna sidelobes, but requires that antenna temperature measurements be made not only of the regions of interest, but also of all those regions which radiate into the antenna sidelobes Normally, an approximate procedure to eliminate the effects of sidelobes is satisfactory. This approximate procedure depends upon the antenna sidelobes being sufficiently small that less than 5 or 10% of the total received power enters the antenna via this path. Then, the energy entering the sidelobes may be treated as a second-order correction, and can be compensated. The resulting inferred brightness temperature then approximately corresponds to an average of that portion of the target area intercepted by the main beam of the antenna. The main beam usually refers to that portion of the antenna pattern within the first nulls. A more complete discussion of these problems has been presented by Staelin[10] and others.

The second step of inferring material parameters from brightness temperatures is more difficult. Although theoretical calculations can provide guidelines for data interpretation, the inherent complexity of natural materials makes mandatory a more empirical approach. To the extent that the relationships between the material parameters and the measured parameters are linear, and the statistics jointly gaussian, we may use optimum linear estimation techniques to infer the material parameters[10]. But to use such techniques we must ultimately determine in a controlled fashion the statistical relationships between brightness temperature and material properties.

REFERENCES

1. J.D. Kraus, Radio Astronomy, McGraw-Hill Book Co., New York, New York, 1966.
2. S. Chandrasekhar, Radiative Transfer, Dover Publications, New York, New York, 1960.
3. D.H. Staelin, Mass. Inst. of Tech., Dept. of Elec. Eng., ScD. Thesis, January, 1965.
4. D.H. Staelin, Proc. I.E.E.E., 57, 4, 1969.
5. J.A. Stratton, Electromagnetic Theory, McGraw-Hill Book Company, New York, New York, 1941.
6. G.E. Marandino, Mass. Inst. of Tech., Dept. of Physics, S.B. Thesis, June, 1967.
7. B.K. Yap, Mass. Inst. of Tech., Dept. of Elec. Eng., S.M. Thesis, February, 1965.
8. A. Stogryn, I.E.E.E. Trans. Ant. and Prop., AP-15, 278, 1967.
9. W. Nordberg, personal communication.
10. D.H. Staelin, Detection and Measurement of Radio Astronomical Signals, Course notes, Mass. Inst. of Tech., 1966.